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AIR VEHICLE INTEGRATION AND TECHNOLOGY RESEARCH (AVIATR)

Task Order 0003: Condition-Based Maintenance Plus Structural Integrity (CBM+SI) Demonstration (April 2011 to August 2011)

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The Boeing Company

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Interim Report

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14. ABSTRACT

This report summarizes progress made on the AVIATR contract Task Order 3, Condition Based Maintenance plus Structural Integrity – Option Phase during the reporting period April 2011 through August 2011. Similar to previous progress reports on this project, the report follows the process detailed in the CBM+SI flowchart. A detailed general purpose flow chart is presented initially, which is followed by a discussion on the specific application for the process on the F-15 wing demonstration. The remaining sections discuss topics within the flowchart that have been tasked during the reporting period. In this progress report tasks related to in-situ sensor system capability analysis, updates to the component level risk analysis and cost benefit analysis are discussed.

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Acronyms/Glossary

CBA	Cost/Benefit Analysis
CBM+SI	Condition-Based Maintenance plus Structural Integrity
DC	Durability Critical Aircraft part(s)
DIR	Directly-Tracked aircraft part
DTA	Damage Tolerance analysis/Assessment
FSMP	Force Structural Maintenance Plan
FST	Full-Scale Test
IATP	Individual Aircraft Tracking Program
IND	Indirectly-Tracked Aircraft Part
IND(L)	Indirectly-Tracked Aircraft Part linked to a directly-tracked part
INS	In-Service
LCC	Life Cycle Costs
MMH	Maintenance Man Hours
MOQS	Maintenance Operational Query System
NDI	Non-Destructive Inspection
NMC	Non-Mission Capable
%NMC	% Fleet Non-Mission Capable
NPV	NET-Present Value
PROF	Probability of Failure; Air Force code used to determine Risk of a part(s)
POD	Probability of Detection
Pr(FA)	Probability of a False Alarm by the in-situ crack sensing system
RBDMS	Risk-Based Design & Maintenance System; Boeing code used to determine Risk of a part(s)
REMIS	Air Force's Reliability and Maintenance Information System
SFPOF	Single Point Probability of Failure
SHM	Structural Health Monitoring
TPM	Technical Performance Measurements
WUC	Work Unit Code

1. Platform Level (Option Phase) Introduction

This report summarizes recent progress made on the AVIATR contract Task Order 3, Condition Based Maintenance plus Structural Integrity (CBM+SI) – Option Phase. Similar to previous progress reports during the Option Phase, the report in general follows the process detailed in the flowchart. A detailed general purpose flow chart is presented in Section 3. This is followed by a detailed application for the general process to our specific application on the F-15 wing demonstration in Section 4. The remaining sections tackle specific topics within the flowchart that have been tasked during the reporting period. In this progress report tasks related to in-situ sensor system capability analysis (Section 5), updates to the component level risk analysis (Section 6) and cost benefit analysis (Section 7) are discussed.

The discussion in Section 5, ”In-situ Sensor Capability Analysis” is a summary of the progress made to understand and represent the detection capability of Structural Health Monitoring (SHM) technologies that could be employed on the F-15 application under consideration. As a starting point, it is based on the methods and assumptions defined in the Department of Defense Handbook on “Nondestructive Evaluation System Reliability Assessment” (MIL-HDBK-1823A).

Section 6, discusses the modifications that have been made to the general risk analysis implementation in the RBDMS code and the detailed analysis for the subset of 16 locations considered initially.. Similarly, Section 7 continues the development of the Cost/Benefit Analysis (CBA) that was started in Phase I with the expansion to consider a number of additional requirements i.e., field inspections vs. Depot inspections, false call rates, etc. As well as expanding the scale to include a number of different locations and application to the 16 location subset.

2. Final Control Point Selections

2.1. March Status

The March 2011 progress report closed with four (out of a possible twelve) aircraft sections suitable for the system-level demonstration: 1) forward center fuselage, 2) aft center fuselage, 3) inner wing and 4) outer wing. These primary structural candidates contained the necessary information to warrant credible and comprehensive analyses as defined by this project's goals. From this list, the chosen candidate's control points would then be identified and the corresponding damage tolerance data applied to the risk and cost benefit analyses.

2.2. Progress and Resolution

Final selection of the remaining candidates depended on several factors including the number of critical locations, access variability of control points, ample history of in-service flaws, and existing F-15 Program risk analyses which pinpointed numerous high risk locations. Further research revealed that both the inner and outer wing together formed an excellent example system.

2.2.1. Consolidation

Table 1 lists the control point tally of the Wing segments along with the associated "criticality". As defined in the March progress report, the criticality of an item is based upon the severity of its impact to the aircraft should the item fail. Direct and Indirect items (*<u>blue and purple coded parts</u>*) refer to items that have a significant effect on the airworthiness of the aircraft. Durability Critical items (*<u>orange coded parts</u>*) refer have a relatively minor impact on the aircraft and immediate replacement (though needed) is not paramount. Additionally, items not established as critical in the FSMP report were re-addressed in the F-15's Program's Silver Bullet Risk Analysis report (Document LF08-084) which attempted to assess the risk of failure for the existing damage tolerance parts. Data within this document provided additional information of higher risk parts that were not previously considered critical in the FSMP report. Incorporating both the C/D and E models, the control point grand total within each section is summed below.

CONTROL POINT TALLY BEFORE A/C MODEL DISECTION (C/D & E)											
Candidates	FSMP "Items of Criticality" Lists (Serv Life < 32K FH)								Risk Document		Grand Total
	DIR	IND(L)	IND	DC	INS	FST (SOF)	FST (DC)	Sub Total	< 32 K (FH)	> 32K (FH)	
Inner Wing	16	8	12	14	0	1	3	54	3	9	66
Aft Center Fuselage	10	5	3	3	0	0	3	24			
Outer Wing	12	3	9	23	0	0	0	47	0	2	49
Forward Center	1	2	0	2	0	0	7	12			

Table 1. Control Point Tally for System-Level Demonstration

2.2.2. Manipulation

Additional steps were performed before the final control point number was determined.

The in-service (INS) and full-scale test (FST) items (brown and green colored cells) were ignored. Neither classification possessed the necessary information to achieve a comprehensive risk analysis. Thus, both were discarded.

The control points of each wing section were divided into C/D and E models. In doing so, a sub-sectional risk vs. cost/benefit analysis could be performed based on aircraft version, establishing a more realistic comparison. As of this writing, only the C/D control points have been applied to this research.

From these steps, the left-sided portions (Grayed cells) of Table 2 and Table 3 itemize the new arrangement. The column "Total Before Triage" lists the control point tally:

C/D model Wing Sections	E model Wing Sections
Inner: 35 control points	Inner: 27 control points
Outer: 31 control points	Outer: 18 control point

One note: Some DTA items documented in the FSMP report possess distinctions within the item itself. Several E version DTA items separate damage tolerance information between aircraft tails (ex: Tails 1-209 versus Tails 210+; both represented by the same DTA number). At this point, there is no differentiation. A reassessment of this issue will occur should the E model become part of the system-level risk analysis.

CONTROL POINT DOWN-SELECT EVOLUTION (C/D Model)														
Candidates	FSMP "Items of Criticality" Lists (Serv Life < 32000 FH)								Risk Document		Total Before Triage	Triage		Projet Control Points
	DIR	IND(L)	IND	DC	INS	FST (SOF)	FST (DC)	Sub Total	< 32 K (FH)	> 32K (FH)		Non DTAs	Add'l Elim	
Inner Wing	8	2	2	14	n/a	n/a	n/a	26	3	6	35	1	5	29
Outer Wing	4	1	7	18	n/a	n/a	n/a	30	0	1	31	8	1	22
										SUM ->	66	9	6	51

Table 2. Control Point Count for Wing Segments (C/D model)

CONTROL POINT DOWN-SELECT EVOLUTION (E Model)														
Candidates	FSMP "Items of Criticality" Lists (Serv Life < 32K FH)								Risk Document		Total before Triage	Triage *(none yet performed)*		Projet Control Points
	DIR	IND(L)	IND	DC	INS	FST (SOF)	FST (DC)	Sub Total	< 32 K (FH)	> 32K (FH)		Non DTAs	Add'l Elim	
Inner Wing	8	6	10	0	n/a	n/a	n/a	24	0	3	27	0	0	27
Outer Wing	8	2	2	5	n/a	n/a	n/a	17	0	1	18	0	0	18
										* SUM ->	45	0	0	45

Table 3. Control Point Count for Wing Segments (E model)

2.2.3. Triage

Once the down-selection process was complete, each control point underwent a "triaged" health examination. This step served two distinct purposes: 1) determined whether or not the control point met a specific minimum requirement defined for this project and 2) established and prioritized the risk sensitivity of those remaining.

The requirement key to this juncture was that the Single Flight Probability of Failure (SFPOF) for a control point never exceeds 1-in-ten-million at any given time during aircraft operation. If, at any flight hour, the control point exceeds this threshold, then the risk to the aircraft was deemed too high for operational use.

To facilitate "triage", damage tolerance data derived from the FSMP report (and from the F-15 Program community) served as inputs into the RBDMS code to map the inspection timelines. The location of this timeline (specifically the slope of the curve in relation to x- and y-axis thresholds) helped determine the sensitivity of the control point to risk analysis. (Details of this relationship are discussed on Section 6.1: Overview of RBDMS.) The control point was discarded from the study if one of two conditions occurred:

- If, at any time, the SFPOF for the control point was greater than 10^{-7} (1-in-ten-million) AND the first inspection interval exceeded the maximum service life of the aircraft (18000 flight hours), then the control point was deemed insensitive for the purposes of this CBM+SI study.

- If the first inspection interval never exceeded the 10^{-7} SFPOF threshold beyond the aircraft's service life (18000 flight hours), then the item was deemed insensitive as well.

The column "Triage" listed in Table 2 and Table 3 specify the number of control points in the Wing segments which were excluded from the risk analysis. Because the E model is not yet considered in this study, triage was not performed. However, the C/D model has undergone a complete triage with a total of 15 items removed from contention. Non-DTA items are those control points which the F-15 Program deemed inconsequential to the airworthiness of the aircraft should these areas fail (if they indeed ever do). Of these "uncounted 9", one resides in the inner wing while 8 reside in the outer wing. The column labeled "Add'l Elim" (or Additional Eliminations) represents the control points involved in triage and were eliminated based on one of the two conditions listed directly above. Five (5) control points were removed from the inner wing risk analysis and one (1) removed from the outer wing. The remaining control points all were deemed sensitive enough for continuation within this study.

3. CBM+SI Process Flowchart

3.1. Purpose/Introduction

Slated as a deliverable is a flowchart depicting the condition-based maintenance process which the structural integrity analysis follows. The flowchart focuses on the application of probabilistic risk analysis to an existing aircraft design, along with the optional application of a specific risk-mitigation technology (i.e. in-situ sensors). The purpose is to provide a blueprint that any organization can duplicate to arrive at a feasible and cost-effective solution.

The flowchart presented in this section is intended to be generally applicable in a CBM+SI setting. In this project, the example failure mode being considered is the growth of fatigue cracks in metallic structure resulting in unstable crack growth. However, the process being developed here could be used for other failure modes, such as composite disbond, corrosion, etc. In addition, this project investigates the use of in-situ fatigue crack detection sensors for mitigation of risk. Any technology which is capable of reducing the risk associated with the failure mode under consideration could be applied here, such as disbond sensors, a new Non-Destructive Evaluation (NDE) technique, an unconventional repair method, etc.

Note that because of the evolving work performed on this contract, the flowchart is under constant revision. As such, the paradigm will be defined at the writing of each progress report. Hence, the August 2011 update defines the flowchart as it stands at this time. Also, it is the intention of the team to produce detail flowcharts that are specific to the in-situ sensor capability analysis, risk analysis, and cost-benefit analysis sections of this report. However, these have yet to be produced.

In the following section the process flowchart shown here will be applied to our specific problem from start to finish using a sixteen location subset of the total list of control points from the wing system. This will facilitate the communication of the use of the flowchart, as well as represent the main narrative of the analysis as it stands. In later sections, each major component of the analysis (in-situ sensor capability analysis, risk analysis, cost benefit analysis) is extensively detailed.

3.2. Flowchart

The following flowchart describes the generalized strategy to perform optimal condition-based maintenance (CBM) analysis with an emphasis on risk analysis and an optional risk-mitigation technology. This includes the definition of the problem, establishment of user-defined parameters, research and gathering of data, as well as the various analyses that must be performed to assist in the decision making process. Figure 1 displays the model.

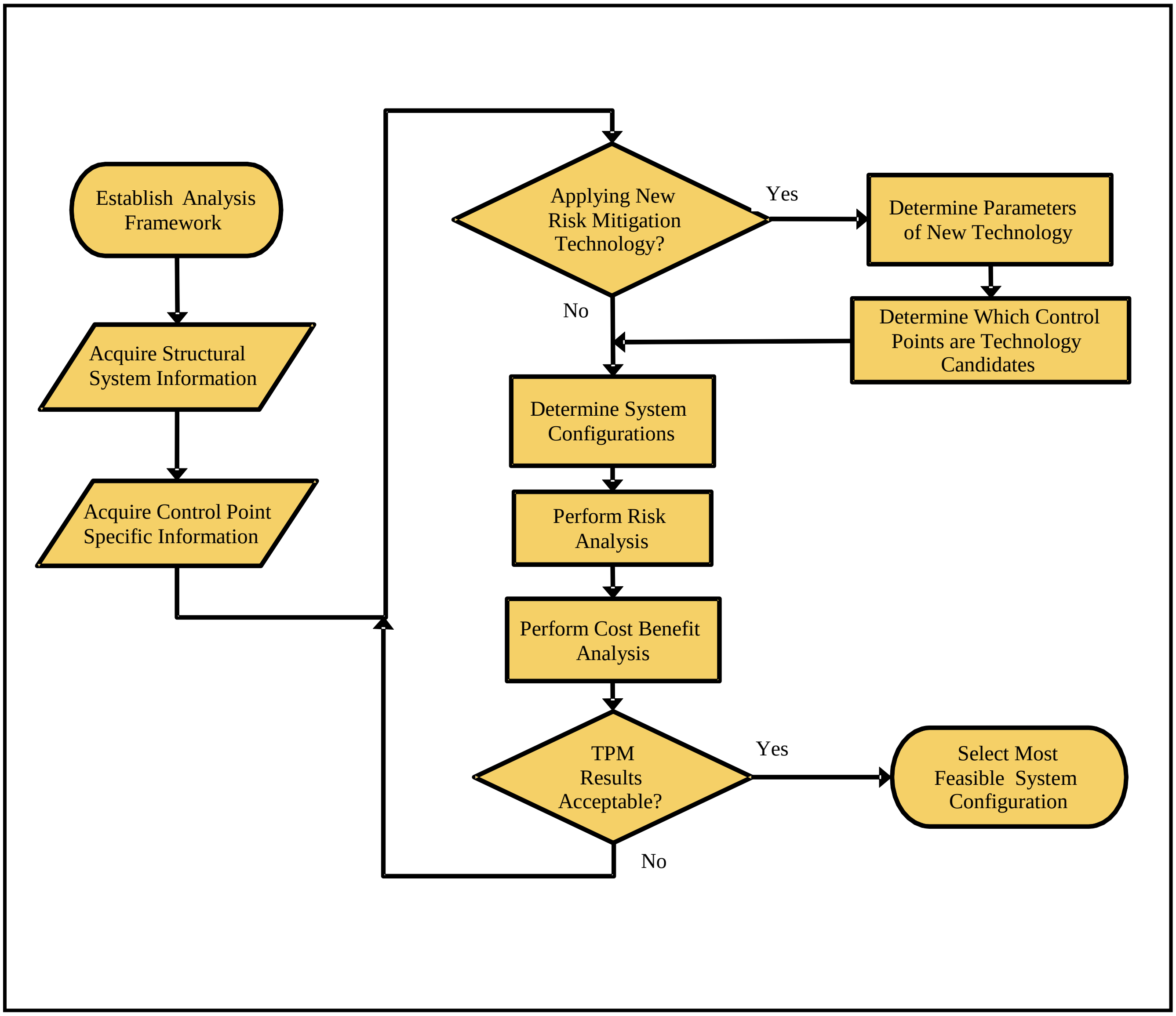
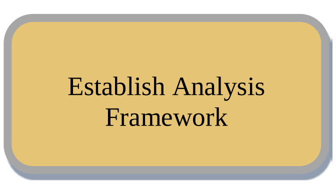


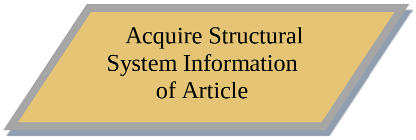
Figure 1. Condition-Based Maintenance plus Structural Integrity (CBM+SI) Process Flowchart

3.3. Flowchart Components

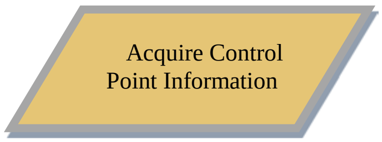
Each flowchart step in Figure 1 is explained below.



Step 1) The strategy for controlling a system's health must abide by the definitions, Technical Performance Measures (TPM), and analyses parameters that the user has established. Without this bounding, determining an optimal strategy is ineffectual. The framework developed is failure mode-specific and, as such, must remain constant throughout the entire analysis process.



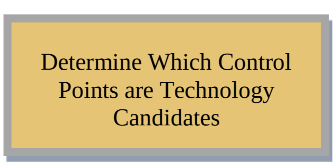
Step 2) Acquiring structural system information refers to any analysis information common to a platform's fleet. Data include fleet size and service life, average hours per flight, control point locations, load spectrums and any other criteria which are independent of tail number or unit.



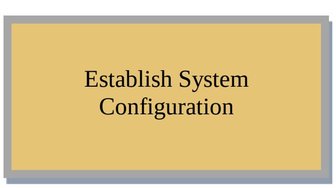
Step 3) Data is collected from all control points relevant to the analyses. Since this step is part-specific, drawings and/or parts lists may be obtained for material characteristics, geometry, and manufacturing process. Resources from Stress or Durability and Damage Tolerance analyses would be obtained as well for risk specific information.

Step 4a) The opportunity to apply advanced risk mitigating technology to the control point is introduced. This is also the first step in the iterative process which allows the user to readjust any inputs, and thus, converge to the ultimate goal of achieving an optimal strategy.

Step 4b) New technologies are researched and introduced to the analysis with the understanding that, with these technologies, each of their capabilities and limitations are defined. Cost of the new technology(s) is investigated and incorporated into the cost/benefit analysis.



Step 4c) Based upon user-defined parameters and/or risk sensitivity, control points are selected for enhancements. Some locations may not be appropriate. For example, a new composite repair method may be utilized but metallic-based control points are not applicable.



Step 5) A baseline system configuration, containing no new or potential technology at any control point, is generated. Cost/benefit TPMs calculated from this baseline serve as a) a reference for comparison and b) a gage for optimization against any other system configuration TPMs. Modified configurations are collections of control points with/without new technology. These TPMs are also calculated and compared against those originating from the baseline.

Step 6) The structural risk analysis must be performed for each feasible configuration using the analyses tools, parameters and definitions defined in step 1.

Step 7) Data generated from the risk analysis are used as inputs for the cost/benefit analysis. Using the technical performance measures (TPMs) defined in step 1, a series of cost calculations is performed for each configuration.

Step 8) The TPMs of the configurations are compared via the cost/benefit analysis (CBA) results. The goal is to determine if at least one configuration is acceptable from regulatory and economic viewpoints. This is the last step in the iterative process before a viable configuration is selected. If no configuration is deemed acceptable, then step 4a is readdressed with knowledge learned from the previous iteration applied to the next iteration(s).

Step 9) If the TPM results for one (or a unique set of) configuration(s) provide satisfactory results, then a decision is made based on a combination of safety and cost.

4. Example Application of CBM+SI Process Flowchart

4.1. Introduction

To demonstrate the method described in Section 3.2 Flowchart, a sixteen location subset of the F-15 Aircraft C/D wing is analyzed as a complete system. A variety of characteristic control points were chosen so that the wing is well represented. Note that the selection of this subset is fully explained in Section 3.3. The focus in this section is on the process which must be followed in order to obtain the information needed to make an informed decision regarding the maintenance strategy and the use of an optionally proposed risk mitigation technology. Each component of the CBM+SI Process Flowchart is discussed here at a high level. Later sections of this report detail the individual components at a more technical level.

4.2. Establish Analysis Framework

4.2.1. Identify the Task

An integrated damage tolerance analysis and structural risk assessment has been proposed for the F-15 fleet. The approach taken here treats the inner and outer wing as a complete structural system. Additionally, the application of an in-situ crack detection technology is investigated. Implementation of this technology into the maintenance framework depends on several factors, including safety of the structural system, cost, and aircraft availability to perform missions. An analysis consisting of risk and cost analyses performed over the entire life of the structural system needs to be performed in order to make an informed decision regarding the optimal maintenance strategy for this structural system.

4.2.2. Specify the Technical Performance Measures & Analysis Parameters

Before collecting and analyzing data, the framework of the analysis must be established to ensure the feasibility of the solution can be quantified and the solution will be acceptable to regulatory authorities.

4.2.2.1.1. Technical Performance Measures (TPMs)

The cost of maintaining the fleet is summarized through the Net Present Value of expenditures (NPV). Note that this represents costs in present day dollars. Thus, a lower NPV is preferable. Note that in finance generally the net present value represents profit and loss, however, in this analysis we are concerned only with costs. Rather than place a negative sign on every value, costs are treated as positive. The net present value is actually the cost of performing all required maintenance over the life of the fleet in today dollars, hence, *lower is better*.

In Phase I the Life Cycle Cost (LCC) was also a TPM. LCC is similar to NPV but does not account for the time value of money. The LCC will be included in more mature reports of this analysis, but is not discussed in this document.

The availability of the aircraft is to be summarized as Percent Non-Mission Capable (%NMC). This parameter indicates the percentage of the life for which the aircraft is incapable of performing missions due to downtime for scheduled maintenance, repairs, or structural failures. The method for calculation of this TPM has not yet been finalized in the cost model. In this document, the expected downtime for the fleet in hours (Fleet DT) is reported instead. This is a simple measure that is closely related to %NMC.

4.2.2.1.2. Risk Threshold

The goal of CBM+ is to establish "evidence of need" at a time just prior to performing maintenance. To fulfill this objective, benchmarks must be established so a comparison between maintenance strategies, and hence a judgment, can be performed. Safety, cost, and availability are the generalized parameters representing this study's benchmarks. Cost, as a TPM, has been discussed in the previous section. Safety and aircraft availability are addressed within the Risk analysis.

Structural safety is characterized by the risk associated with the SFPOF for each control point. This term is the statistical representation of the likelihood of a part (or control point in this case) to catastrophically fail during flight. MIL-STD-1530C documents the values which the SFPOF must not exceed:

"A probability of catastrophic failure at or below 10^{-7} per flight for the aircraft structure is considered adequate to ensure safety for long-term military operations. Probabilities of catastrophic failure exceeding 10^{-5} per flight for the aircraft structure should be considered unacceptable. When the probability of failure is between these two limits, consideration should be given to mitigation of risk through inspection, repair, operational restrictions, modification, or replacement."

The language of MIL-STD-1530C suggests that the 10^{-7} threshold applies to *the structural system*. At this stage of the analysis, this threshold is applied to each control point individually, rather than to the system as a whole. It is believed that a thoroughly performed component-level approach will facilitate a system-level approach.

4.2.2.1.3. Analysis Tools

The deterministic damage tolerance analysis, which must be performed prior to the risk analysis, is conducted using LifeWorks, a Boeing Proprietary tool for Crack Initiation and Crack Growth Analysis. The bulk of this analysis has already been performed by the F-15 Program, but some re-work was requested during the project.

The tool used to perform the risk analysis (calculation of SFPOF and other required information) is the Boeing Proprietary tool RBDMS (Risk-Based Design and Maintenance System). The methodology of this tool is discussed in the Risk Analysis section of this report, Section 6.

Microsoft Excel is used to conduct the CBA.

4.3. Acquire Structural System Information

4.3.1. Fleet Parameters

Several fleet characteristics are required for the risk and cost analyses. For this analysis the most relevant fleet parameters are regarding the usage of the aircraft. The current spectrum, FTA6, is the most recent iteration of the typical aircraft usage. This spectrum represents a significant increase in usage severity over the previous spectrum (FSMP). Other usage parameters provided by the F-15 program are as follows: the typical platform flies 300 flight hours (FH) per year at 1.3 FH per flight. The service life for the 300 aircraft fleet is assumed to be 18,000 FH, and this analysis is currently being conducted under the assumption that each platform is pristine. That is, this analysis is theoretically being conducted at the beginning of the life of the fleet. Note that the choice of the 18,000 FH service life will affect the analysis as costs will be spread over 60 years (300 FH per year). The sensitivity of the results of this analysis to the choice of lifetime will be investigated at a later stage of the project.

4.3.2. Maintenance Parameters

The F-15 Program has indicated that, in practice, maintenance actions are generally performed on flight hour multiples of 200. For example, if an NDE inspection is scheduled to occur at 1116 FH, it will in actuality be performed at 1200 FH. To maintain as much realism as possible, all traditional NDE inspections and repairs will take place on 200 FH increments.

Programmed Depot Maintenance (PDM) occurs every six calendar years. PDM occurs at the depot (as opposed to in the field). At this time the aircraft undergoes significant maintenance on several systems (including the structural system). Many locations in the wing cannot be accessed in the field due to significant obstruction of structure and materials. Therefore traditional NDE inspections and repairs cannot take place for certain locations outside of PDM.

In this document, locations are distinguished between those easily accessed in the field and those which cannot. The easily accessed locations are referred to as field-accessible. The remaining locations, only accessible at PDM, are referred to as depot-accessible. Of course, it is implied that the field-accessible locations can also be easily accessed at PDM.

The accessibility of a location has significant implications when contemplating the application of in-situ sensors. These sensors permit “inspection” at any time regardless of location. However, repairs cannot be reasonably performed in the field. In addition, all technology-assisted inspection methods include the possibility of false positives which cannot be distinguished from true crack detections. Each time a decision to repair is made in the field for a location that is impossible to access; the wing must be disassembled and shipped to the depot for repairs. This disassembly is very expensive and causes the aircraft to experience significant downtime. Therefore, the implications of this possibility must be accurately represented in the cost/benefit analysis. These penalties are discussed in detail in Section 7 – Cost Benefit Analysis.

The in-situ inspections are assumed to take place at either 300 or 600 FH intervals. It is required that the intervals overlap those of the PDM cycle (1800 FH). The chance of false call occurrences increases with the frequency of inspections, so the risk analysis team is using 300 FH as an operating minimum and using 600 FH intervals if possible. This will be discussed in more detail in Section 4.6.

4.3.3. Cost Parameters

There are numerous cost parameters relevant for estimating the cost of maintaining a fleet of aircraft, such as the hourly labor rate for maintenance, the discount rate used for computing present and future values, etc. In addition, many of the parameters pertain to the installation and maintenance of an in-situ sensor system. A complete list of inputs required by the cost model, along with detailed explanations, is located in Section 7.

4.4. Acquire Control Point Specific Information

The information specific to each individual control point required to conduct the risk and cost analyses are gathered at this stage of the flowchart. Some of the required information is shown below in Table 4 to give the reader a sense of what information needs to be gathered. The control points are referred to by Damage Tolerance Assessment (DTA) number, and organized in the table according to the accessibility of the location. This accessibility is of paramount importance in determining a maintenance schedule as many locations can only be accessed in the depot when the aircraft is significantly disassembled for internal maintenance. In addition to that which is shown, a damage tolerance crack growth analysis is required for each control point. The *similar locations* refer to the number of locations for which the crack growth analysis can be thought to pertain to. For example, a part may possess 10 fastener holes, and each of the two wings may contain this part, so the crack growth analysis for that location refers to 20 similar locations.

DTA	Accessibility	Similar Locations	Small Crack Repair Time	Medium Crack Repair Time	Large Crack Repair Time	Cost of Part Replacement
055	Field	36	8 (hrs)	60 (hrs)	160 (hrs)	$50,000
057B	Field	32	8	84	160	60,000
164	Field	154	60	60	240	100,000
165	Field	32	60	60	240	100,000
166B	Field	2	24	60	240	100,000
184	Field	48	8	40	160	40,000
187	Field	134	10	60	160	40,000
188	Field	20	8	60	200	40,000
097	Depot	2	12	NA	200	100,000
115	Depot	95	8	32	72	5,000
124B	Depot	12	8	60	160	50,000
134B	Depot	8	8	40	120	40,000
138B	Depot	4	8	40	120	40,000
143	Depot	2	4	32	160	20,000
144	Depot	2	24	40	60	5,000
203	Depot	2	12	80	160	50,000

Table 4. Summary of Control Point Data for 16 Location Subset

4.5. Risk Mitigation Technology

4.5.1. Apply New Risk Mitigation Technology?

At this point of the flowchart various technologies may be considered for implementation in the system. In this analysis, the use of an in-situ crack detection system which has capability similar in scope to that of traditional NDE is considered.

4.5.2. Determine Parameters of New Technology

With any technology-assisted crack detection system, there is a trade-off between the detection capability and the Probability of a False Alarm (henceforth Pr(FA)). The reason for this, along with the development of these Probability of Detection (POD) curves in general, is detailed in Section 5.

Three different POD curves pertaining to the in-situ crack detection system are utilized at this stage of the analysis, each with an associated Pr(FA). These compare well with the two POD curves utilized for risk analysis by the F-15 Program, which we are using for NDE inspections on this project. Figure 2 below depicts the five POD curves that are used in the analysis of the 16 location subset, and the median detection capability and false call rate for these curves are shown in Table 5. The F-15 curves are labeled as F-15 HF and F-15 LF, referring to the high fidelity and low fidelity NDE curves, respectively. The in-situ POD curves are similarly named In-situ HF, MF, and LF, for high, medium, and low fidelity, respectively.

Interpretation of a POD curve is as follows: for an existing crack of a given size (found along the x-axis), the curve gives the probability that it will be detected in a single inspection (the y-axis). The label of the y-axis, POD | a, refers to the probability of detection for a given crack size, a. For example, consider the Pr(FA)=0.001% curve in Figure 2 (the red, long dashed line). For this curve, a crack of size 0.05" has around a 30% chance of being found, and a crack of size 0.10" will be detected in over 90% of inspections.

Name	Median Detectable Crack (in.)	False Call Rate
F-15 HF	0.025	?
F-15 LF	0.050	?
In-situ HF	0.039	1%
In-situ MF	0.044	0.1%
In-situ LF	0.054	0.001%

Table 5. POD Curve Parameters

The false calls rates associated with the NDE inspections currently utilized for maintenance of the F-15 fleet are not yet known. The subject matter expert for determining this has been identified but has not yet provided this information.

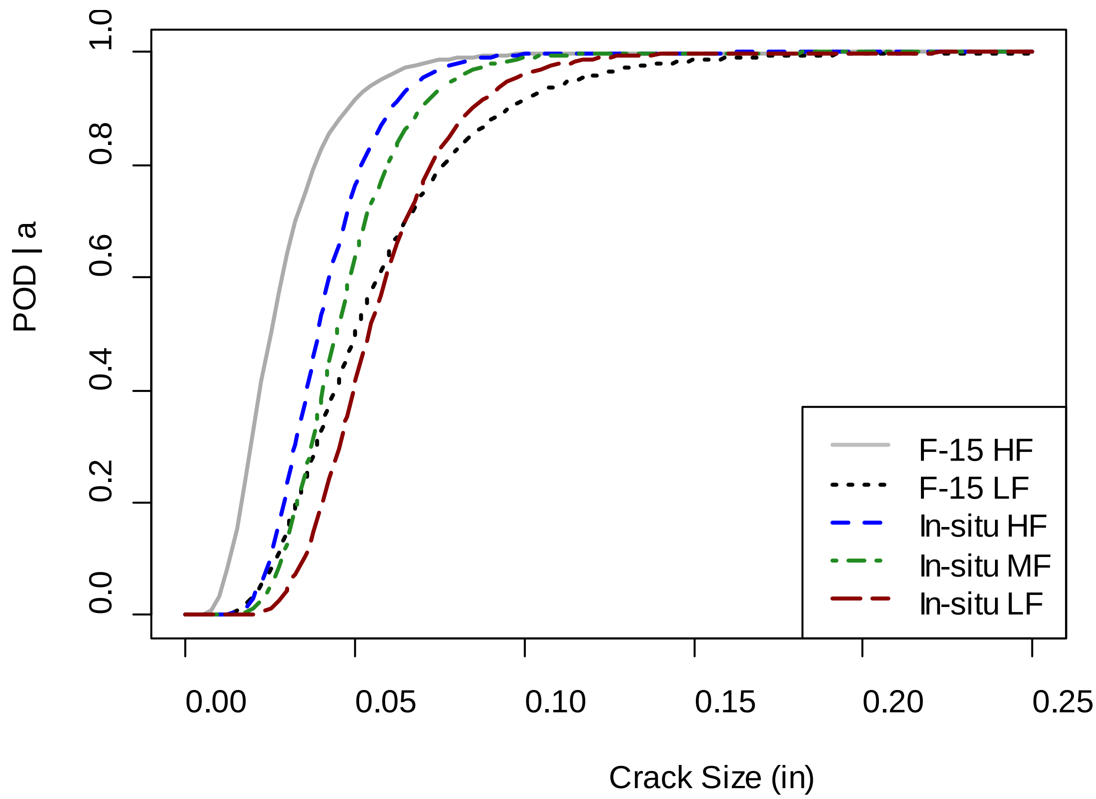


Figure 2. Plot of POD Curves Used in Analysis of 16 Location Subset

4.5.3. Determine Which Control Points are Technology Candidates

The team's subject matter expert examined each control point and determined that all sixteen locations fit the criteria for the in-situ sensor system under consideration. However, several of these locations are likely to be low in risk, which makes it doubtful that installation of sensors will prove to be cost effective. That is, while all locations are candidates for the technology, several locations may be dropped as candidates in either the *Perform Risk Analysis* or the *Perform Cost Benefit Analysis* sections of the flowchart.

4.6. Determine System Configurations

The current maintenance practice in use in the field is referred to as the Baseline configuration. This includes NDE inspections at each location with inspection times defined using traditional deterministic damage tolerance methodologies.

The Risk-Based configuration is similar to the Baseline. However, the inspection times are now defined by the SFPOF. That is, for each location, an inspection does not occur until the risk approaches the 10^{-7} threshold. Note that several of the depot-only locations in the subset do not have a risk-based scenario due to the fact that they are already inspected at every PDM and the risk is not sufficiently low to decrease the frequency of inspections.

The two configurations described above do not include the in-situ sensor system. When considering this technology, a large number of configurations can exist as each location may or may not have the sensors installed in a given configuration. In addition, there are several POD capabilities which can be assigned to each location. Suppose there are 3 options for each location: no in-situ sensors, in-situ with high fidelity POD, and in-situ with low fidelity POD. If there are 16 locations, there are a total of 3^{16}, or more than 40 million, possible configurations. Hence it is infeasible to perform the risk and cost analyses for every possible configuration. The number of acceptable scenarios for each DTA item must be limited in order to limit the total number of potential configurations which must be analyzed. Several rules to that effect are as follows:

- Field-accessible locations use a single in-situ POD curve over the life
    - The POD used for a given location will not change partway through the life
- Depot-accessible locations use at most two in-situ POD curves over the life
    - A higher fidelity system may be used when the aircraft is at the depot
        - The increased Pr(FA) is acceptable at the depot
    - A lower fidelity system may be used when the aircraft is in the field
        - This is preferable since there are large penalties associated with crack detections and false alarms when repairs must be performed in the field
- In-situ inspection timing is limited to two intervals: 300 FH and 600 FH
    - These timings are chosen such that the in-situ inspections will overlap with the PDM cycle (1800 FH intervals)

When a depot-accessible location requires a repair in the field, there is a problem. The location cannot be accessed, but the sensor system has detected a crack. Shipping the aircraft to the depot for a single repair (which may be a false alarm) is infeasible. After discussion with the F-15 Program, it was determined that the best option for performing the repair is to remove the wing in the field, replace it with a spare wing that is kept on hand in the field, and ship only the wing to the depot for repair. This method carries with it two penalties which are accounted for in the cost model. A repair penalty of 500 man hours is added on to the time for repair, which includes shipping costs for the wing. A downtime penalty of 8 hours is applied, which reflects the time required for a team to remove and replace the wing. The 500 man hour penalty is severe, hence a method which allows for the majority of cracks to be detected when the plane is at the depot (where no penalties apply) would be beneficial. The cases in which a lesser fidelity POD is used in the field, and a high fidelity POD is used at the depot, are referred to as *Mixed* cases.

The available options for each of the 16 DTA items in the subset are limited to those listed below in Table 6. Note that the mixed cases are only considered for use with the depot-accessible items.

Abbreviation	Inspection Type	Pr(FA)	Inspections
Base	Baseline NDE	Unknown	Traditional
Risk	Risk-based NDE	Unknown	Risk-based
HF3	High Fidelity In Situ	1.0%	300 FH
HF6	High Fidelity In Situ	1.0%	600 FH
MF3	Medium Fidelity In Situ	0.1%	300 FH
MF6	Medium Fidelity In Situ	0.1%	600 FH
LF3	Low Fidelity In Situ	0.001%	300 FH
LF6	Low Fidelity In Situ	0.001%	600 FH
MixHL3	Mix of High & Low Fidelity	1.0% / 0.001%	300 FH
MixHL6	Mix of High & Low Fidelity	1.0% / 0.001%	600 FH
MixML3	Mix of Medium & Low Fidelity	0.1% / 0.001%	300 FH
MixML6	Mix of Medium & Low Fidelity	0.1% / 0.001%	600 FH

Table 6. Scenario Options for Each DTA Item

A single *configuration* consists of a selection of one of the above options for each DTA in the subset. There are far too many potential configurations to consider them all. Engineering judgment must be used to limit consideration to those configurations which are likely to be competitive when comparing TPMs. That is, an attempt is made to find options for each DTA item that are obviously superior to the other available options (lower risk, fewer required inspections, etc). To do this, RBDMS is run for each option of each location. Then the risk results are compared and the inferior solutions are dropped from consideration. For example, see the SFPOF plots for DTA 187 in Figure 3 below (only the peaks are shown for clarity). Recall, DTA 187 is field-accessible, so the mixed options are not considered. Also, the high fidelity options are a last resort, and they were not required to be run for this location. Here, the 600 FH interval options do not sufficiently reduce the risk and are dropped from consideration. Either 300 FH interval option will suffice, hence they are both retained.

This process is carried out for each DTA item and a small number of options are retained for each location. In Table 7, the DTA items and the available options are placed in a matrix and the selections which are retained are indicated with an “X”.

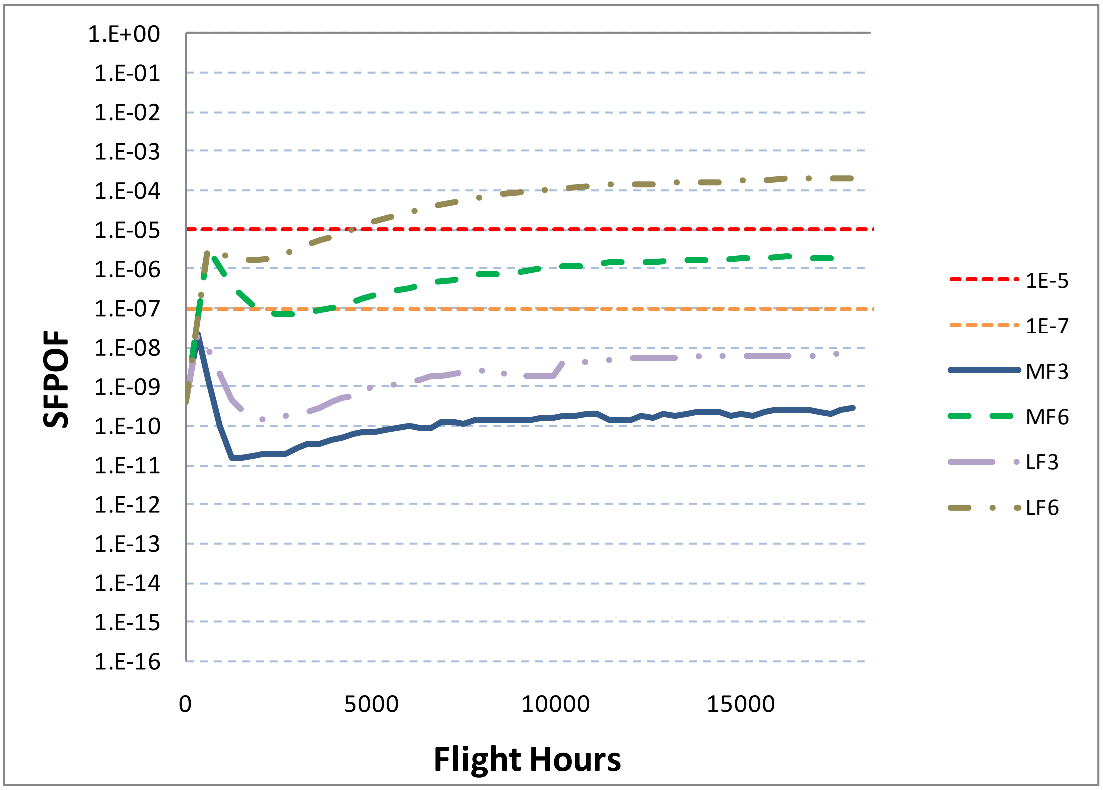


Figure 3. Peak SFPOF Plots for DTA 187

	Base	Risk	HF3	HF6	MF3	MF6	LF3	LF6	MixHL3	MixHL6	MixML3	MixML6	# to permute
055	X	X					X						2
057B	X	X						X					2
097	X	X											1
115	X								X				1
124B	X							X					1
134B	X				X				X				2
138B	X								X				1
143	X							X				X	2
144	X				X				X				2
164	X	X					X	X					3
165	X	X					X	X					3
166B	X	X											1
184	X	X			X		X						3
187	X	X			X		X						3
188	X	X						X					2
203	X	X											1

Table 7. Maintenance Options Retained for Each DTA Item

The Base case refers to the baseline configuration in which each DTA item uses the *Base* option. The SFPOF of several of the baseline scenarios is excessively high. This causes the TPM results for the Baseline scenario to be unrealistically high. This makes comparison of the other cases to the baseline case difficult at this time. The high risk issue is discussed in Section 6.5.

Note that several of the DTA items do not have a *Risk* case. These are depot-accessible items that are already inspected in the baseline at every PDM and which have risk levels that are too high to allow for fewer inspections. At this time, the benefit of the *Risk* configuration can only be approximated as those DTA items which do not have a *Risk* option use the *Base* option instead.

The matrix shown above is used to create a complete permutation of all of the in-situ configurations which will be considered. The *Base* options are not utilized when performing this permutation, hence the final column in Table 7 shows the number of options which will be considered for each DTA item for use in the in-situ configurations. The total number of configurations to be considered is the product of this column: 5184 configurations. The statistical software *R* is used to perform this permutation. When also considering the baseline and risk-based configurations, a total of 5186 configurations are run, of which one or several will be recommended for use as the system configuration.

4.7. Perform Risk Analysis

Each checked box in Table 7 corresponds to a single RBDMS run. Hence there are a total of 46 RBDMS results files that are to be used in the cost model. Each configuration consists of 16 sets of RBDMS results (one per DTA item). Section 6 of this report discusses the use of RBDMS for risk analysis. An example output file is shown in Table 8. Only those results which are utilized in the CBA are shown here.

No	CumFH	InspType	PFSLBI	PFSLAI	PCDsmall	PCDmed	PCDlarge
0	0	0	.1776E-14	.0000E+00	.0000E+00	.0000E+00	.0000E+00
1	7200	1	.8451E-08	.1266E-13	.6098E-01	.6414E-01	.1213E-01
2	12600	1	.4988E-08	.1510E-13	.9438E-01	.8552E-01	.1469E-01
3	18000	1	.5242E-08	.4130E-13	.2104E+00	.2261E+00	.1677E-01

Table 8. Example RBDMS Output; DTA 203 Risk Option

The inspection number is in the first column, followed by the inspection times. The SFPOF before and after inspection are labeled PFSLBI and PFSLAI, respectively. The final three columns give the probability of detecting a crack of small, medium, or large size at each inspection. These are used in the cost model as larger cracks are much more expensive to repair. Note that at time zero (inspection # 0) no inspection is performed. However, there is an initial risk level based on the potential for flaws that are present at time zero.

4.8. Perform Cost Benefit Analysis

In this section the costs associated with each of the 5186 configurations for each DTA are summarized. The mechanics of the cost benefit analysis are discussed in Section 7 of this report. Note that these results are preliminary. It is not the intention of the team that the numbers presented here be disseminated to the SHM community as evidence for or against the use of in-situ sensors. Issues remain which are known to skew the results. In particular, several of the Baseline configurations exhibit very high risk. This causes the Baseline cost estimates to hyper-inflate as an unrealistic number of part failures is predicted. Six of the locations in the sixteen location subset contain interference fit fasteners, for which a method for significantly reducing the risk has been determined but not yet implemented. This is discussed in Section 6.5.1 of this report.

As described above, the cost model is a Microsoft Excel-based tool. This workbook performs the cost analysis for a single configuration. The TPMs for each of the 5184 in-situ configurations are calculated by automating the import of configuration parameters and output of results via a macro using Microsoft's programming language Visual Basic for Applications (VBA). In brief, this is performed by tabulating each configuration to be examined and programmatically stepping through each configuration by importing the appropriate RBDMS results, updating the cost parameters for each DTA item, and tabulating the resulting TPMs. This macro takes a fraction of a second to parse each configuration and the process of performing the calculation for all 5184 configurations takes roughly 22 minutes.

The in-situ configurations with the lowest NPV (present value of the costs, *lower is better*) and the lowest total expected fleet downtime are shown below in Table 9. The fleet downtime is shown rather than the %NMC because the method for calculating %NMC has not yet been finalized.

DTA	Accessibility	Min NPV	Min Fleet DT
055	Field	Risk	Risk
057B	Field	Risk	LF6
164	Field	LF3	LF3
165	Field	LF6	LF3
166B	Field	Risk	Risk
184	Field	Risk	Risk
187	Field	MF3	MF3
188	Field	LF6	LF6
097	Depot	Risk	Risk
115	Depot	MixHL3	MixHL3
124B	Depot	LF6	LF6
134B	Depot	MixHL3	MF3
138B	Depot	MixHL3	MixHL3
143	Depot	MixML6	LF6
144	Depot	MixHL3	MF3
203	Depot	Risk	Risk

Table 9. In-situ Configurations with Minimum NPV and Fleet Downtime

The NPV and expected fleet downtime of the baseline, risk-based, and most preferable in-situ configurations are shown in Table 10 below. To re-iterate, the Baseline configuration results are inflated due to the high risk of several locations and are not useful for comparison at this time. Six of the sixteen locations will soon see significant alteration of the risk as they include interference fit fasteners, the effect of which has not yet been incorporated in the crack growth analysis. This alteration is discussed in Section 6.5.1.

Configuration	NPV ($b)	Fleet DT (hrs)
Baseline	219.209	7,840,241
Risk-Based	3.533	6,208,154
In-situ; Min NPV	1.284	3,732,946
In-situ; Min Fleet DT	1.370	3,676,031

Table 10. TPMs of the Baseline, Risk-based, and Preferred In-situ Configurations

For purposes of comparison, note that the highest (worst) NPV for an in-situ configuration was $1.42 billion, and the maximum fleet downtime for an in-situ configuration was 4.9 million hours.

4.9. TPM Results Acceptable?

As previously stated, some unresolved issues remain which make it difficult to determine the benefit of the in-situ system, namely the high risks associated with the baseline for several locations and the lack of a risk-based option for some depot-accessible items.

If the numbers presented here were thought at this time to be correct, a re-design of several DTA items would be required in order to produce an acceptable configuration that does not include the use of an in-situ sensor system. That is, of the baseline, risk-based, and in-situ configurations, only the in-situ configuration is capable of maintaining the risk of each location below the prescribed threshold. Hence, only the in-situ system configurations are acceptable according to the framework described in Section 4.2 – Establish Analysis Framework.

4.10. Select a Feasible Configuration

At this stage of the analysis, the in-situ configuration corresponding to the minimum NPV as described in Table 9 would be recommended for maintenance of the 16 location F-15 wing system. This choice would be made due to the fact that the NPV is $80 million lower and the fleet downtime is only 1.5% higher than the minimum fleet downtime configuration. If fleet availability were determined to be the more important parameter, the other configuration could be selected. Furthermore, several configurations fall in between these values, thus one could choose to carefully examine more candidate configurations to make a decision. In this preliminary example these two cases suffice for demonstration.

5. In-Situ Sensor Capability Analysis

The detection performance of inspection techniques is usually measured by a Probability of Detection (POD) metric which is a probabilistic representation, or model, of the likelihood that the inspection will find damage of a certain size. As certain risk analysis cases show, a benefit could be realized by having the ability to detect damage more often than traditional ASIP inspection cycles. If in-situ automated technologies (such as SHM) are introduced to do these inspections their performance will need to be evaluated in terms of metrics that can be used to determine their detection performance as well as quantify their development and operational costs.

The following is a summary of the progress made to-date in attempting to understand and represent the detection capability of SHM technologies that could be employed on the F-15 application under consideration. As a starting point, it is based on the methods and assumptions defined in the Department of Defense Handbook on "Nondestructive Evaluation System Reliability Assessment" (MIL-HDBK-1823A). Note that the subject of POD for in-situ detection systems is an active research area and is by no means fully understood. To that end, since the risk analysis research in this project is the "end user" of the detection data it is critical that the risk analysis drive the requirements (and assumptions) needed to accurately model the detection data.

5.1. Probability of Detection Approach of SHM

One necessary precondition for certifying a SHM system for flight is being able to provide a rigorously obtained Probability of Detection (POD) curve. The POD curve provides information about the smallest crack size that can be reliably detected by an inspection system.

There are two significant questions that must be answered about the performance of a SHM system in terms of POD. The first question is: What is the smallest size crack that can reliably be detected? This crack size is expressed as $a_{90/95}$ where the 'a' refers to the crack length, '90' refers to the detection rate, and '95' refers to the confidence level. The confidence level is a statistical concept that quantifies the uncertainty in the estimation. Taken together, this means that there is 95% confidence that the system will detect *at least* 90% of the cracks of length $a_{90/95}$.

The general process for obtaining these measures is briefly described below. Typically one would establish a relationship between an inspection system's output (usually termed $\hat{a}$) and the "true" measured crack length, a. For these studies, the relationship is established between the SHM system's Damage Index (DI), which will be called $\hat{a}$, and the measured crack length, a. This relationship is established using linear regression as follows. Let $x = f(a)$ and $y = g(\hat{a})$ where f and g are either linear or logarithmic functions selected such that x and y are linearly related. The linear or logarithmic representation of the DI, y, is then estimated as:

$$y = \beta_0 + \beta_1 x + e \tag{1}$$

where β_0 and β_1 are coefficients to be solved for and e is the residual error which is normally distributed with a zero mean and a variance δ^2.

The selection of an appropriate detection threshold, y_{th} , is described below. Let $\Phi(z)$ be the standard normal cumulative distribution function and let $Q(z)$ be the survivor function, equal to $1-\Phi(z)$. The POD function can then be derived as:

$$POD(a) = P\left(y > y_{th}\right) = 1 - Q\left[\frac{f(a)-u}{\sigma}\right] = \Phi\left[\frac{f(a)-u}{\sigma}\right]$$

$$where \quad u = \frac{\left(y_{th} - \beta_0\right)}{\beta_1} \quad and \quad \sigma = \frac{\delta}{\beta_1} \tag{2}$$

This formula provides the probability of detection for any given crack size, a. Statistical techniques can be used to calculate the 95% confidence interval of this POD curve and the $a_{90/95}$ point can be selected. One option for generating the POD curve is to use software based on MIL-HDBK-1823A "Nondestructive Evaluation System Reliability Assessment" available for free download [4].

5.2. False Call Rate

The second major question involves determining the probability of a false alarm (i.e. how often the system indicates a crack when one does not exist). The probability of false alarm is denoted as *Pr(FA)*. Calculation of *Pr(FA)* is accomplished by collecting and characterizing a given SHM system in the situation where no crack exists. Due to in-situ environmental effects, DI measurements taken when no crack exists will have an average value greater than zero. This background noise can be characterized by a specific probability density function (DI Noise PDF) using statistical techniques. This PDF allows the calculation of the probability that a given 'no crack' DI value exceeds the detection threshold as shown in Figure 4 as the shaded 'Probability of False Alarm' area of the DI Noise PDF. The shaded portion represents the proportion of times a 'no crack' DI value will exceed the detection threshold. Similarly, integrating the portion of the DI scatter PDF that lies above the detection threshold provides POD(a) since that portion of the function represents the proportion of times a DI for a given size crack will exceed the detection threshold.

Both the detection threshold, y_{th}, and *Pr(FA)* can be calculated explicitly as a function of one another. As an example, assume the noise has been analyzed and found to have a normal distribution with mean μ and standard deviation σ. For a given probability of false alarm, the detection threshold can be calculated as:

$$y_{th} = \mu_{noise} + \sigma_{noise}\Phi^{-1}(1 - Pr(FA)) \tag{3}$$

Conversely, the probability of false alarm can be calculated as:

$$Pr(FA) = 1 - \Phi\left(\frac{y_{th} - \mu_{noise}}{\sigma_{noise}}\right) \tag{4}$$

where Φ represents the normal cumulative distribution function.

As shown in equations above and Figure 4, background noise is one of the major factors that determines false positive rates and overall performance of a SHM system. Understanding key noise contributors and developing solutions to mitigate them are the focus of future design improvement and performance characterization efforts.

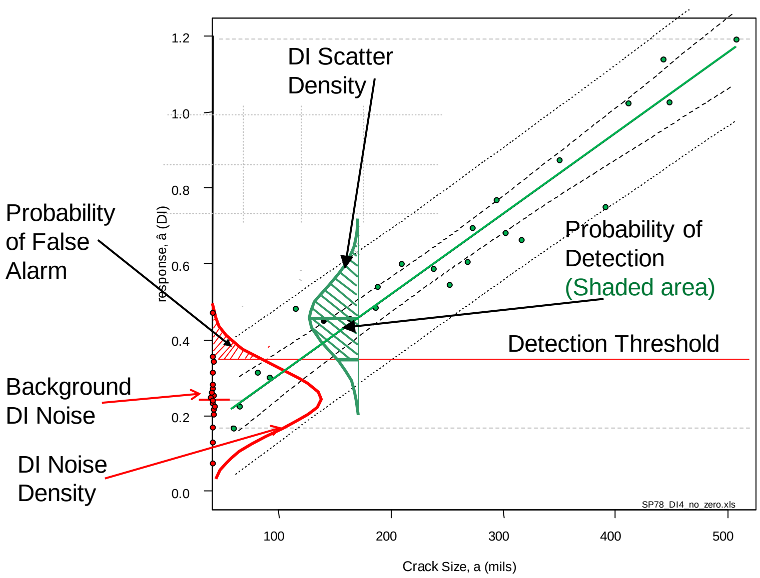


Figure 4. Sample *Pr(FA)* calculation based on background noise

5.3. POD Curve/False Call Examples from AFRL Hot Spot Program using MIL-HDBK-1823A POD Software

The process of creating a POD curve based on a vs. a-hat data can be accomplished using POD software. Software based on MIL-HDBK-1823A is available free by download from the author (Charles Annis, P.E) who developed it as part of a DOD contract to write the latest version of MIL-HDBK-1823A.

The following pages will provide an example of creating a POD curve with data from a series of SHM experiments on six identical test specimens. Only three inputs are needed: *a*, *â* and background as defined in previous section.

Figure 5 shows the DI value vs. crack length plotted vs. various axes. Ln X and Ln Y were selected as the best linear representation of the data. A linear relationship is needed to have a valid linear regression model. One consequence of having a linear model approximate non-linear data is that the properties of the error of the model would vary as a function of input value. Analysis done with linear regression models assumes a constant standard deviation of the scatter error. With non-linear data this would not be true; some portions of the model would have a very high standard deviation and other very low.

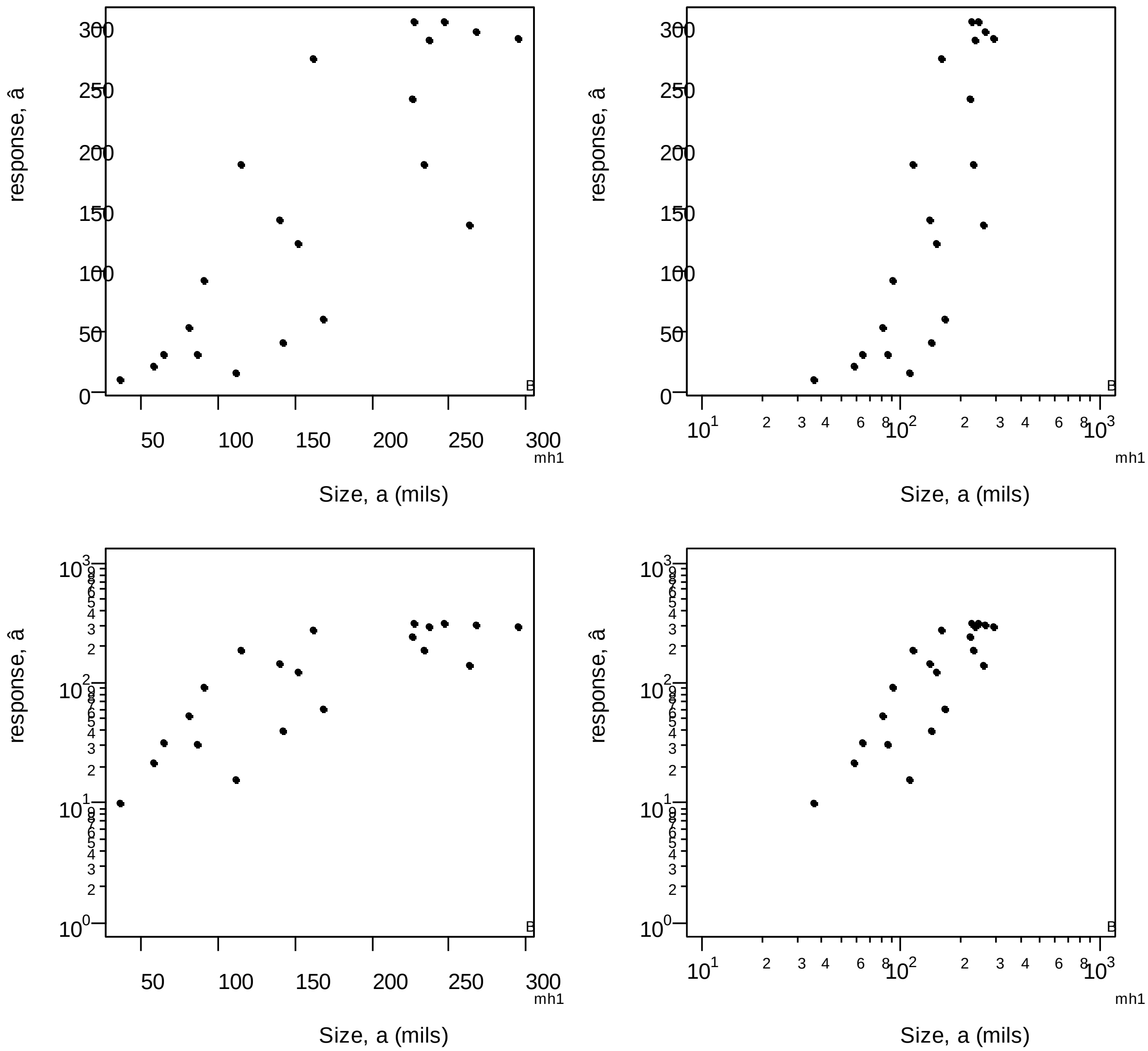


Figure 5. DI value (*â*) vs. crack length (*a*) plotted on linear-linear, log-linear, linear-log, and log-log axes

Figure 6 shows the regression model of the selected axis types of the of the system response $\hat{a}$ as a function of crack size '*a*' with a 95% confidence interval. Note that a log scale was chosen for each axis. This plot shows left (9.805) and right (304.323) censors value lines. The left censored was selected as the smallest crack size in the data set. The right censored value was selected as the maximum crack values of the data set. The decision threshold was set to 12.57 mils which corresponds to a false alarm rate of 0.1%. This will be adjusted later on. The decision threshold is defined as the value of $\hat{a}$ above which the signal is interpreted as a hit, and below which the signal is interpreted as a miss. It is the $\hat{a}$ value associated with 50% POD.

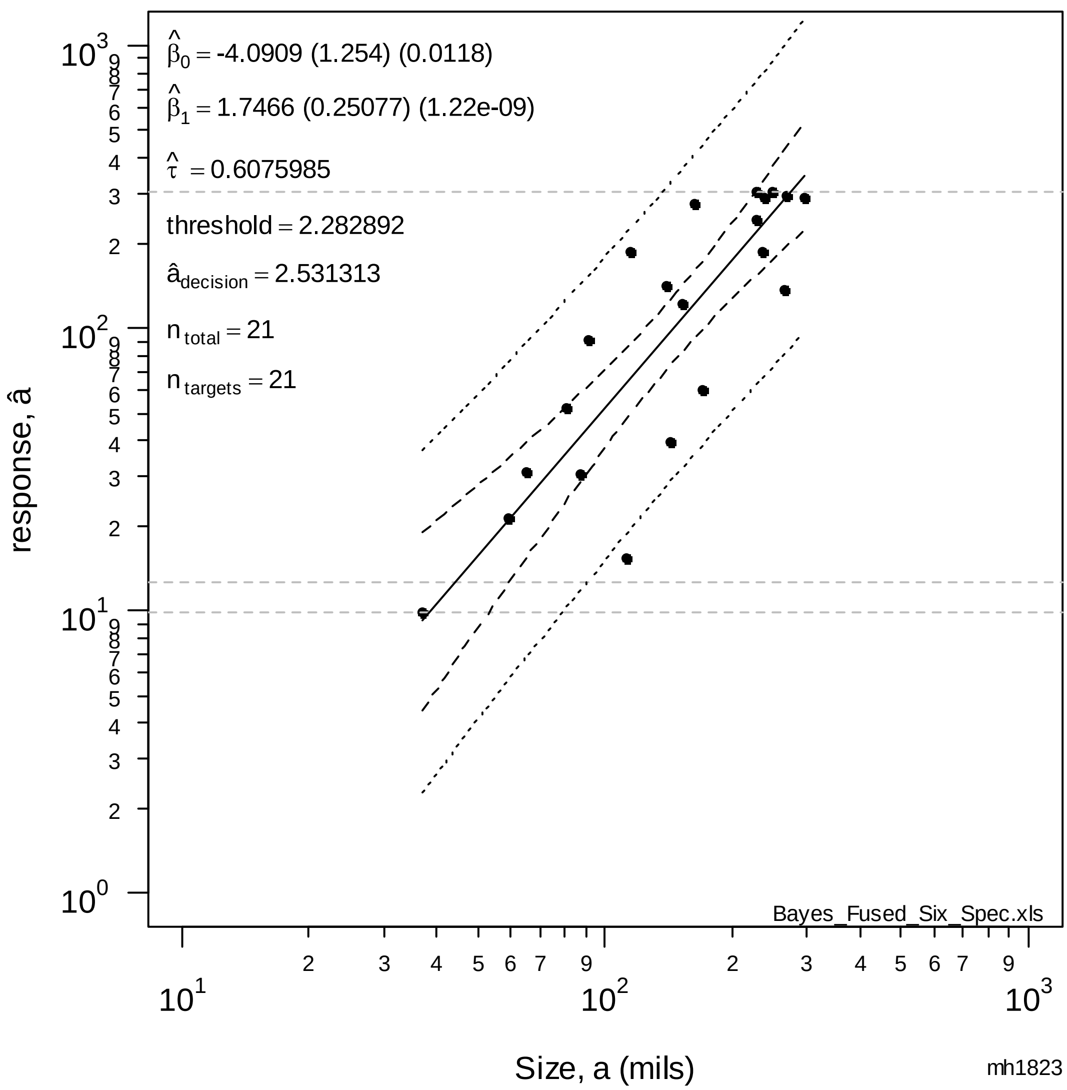


Figure 6. A regression model of '*a*' vs. '*â*' data from the selected axis type with 95% confidence interval about line (the inner dashed lines) and scatter (the outer dashed lines)

Figure 7 shows noise data plotted on four different types of probability ‘paper’. The natural log distribution appears to be the best background noise model. Figure 8 shows a magnified version of Figure 7d showing a close-up of the probability distribution plot. It represents the selected form of the distribution (for later analysis) and provides values for the distributions parameters.

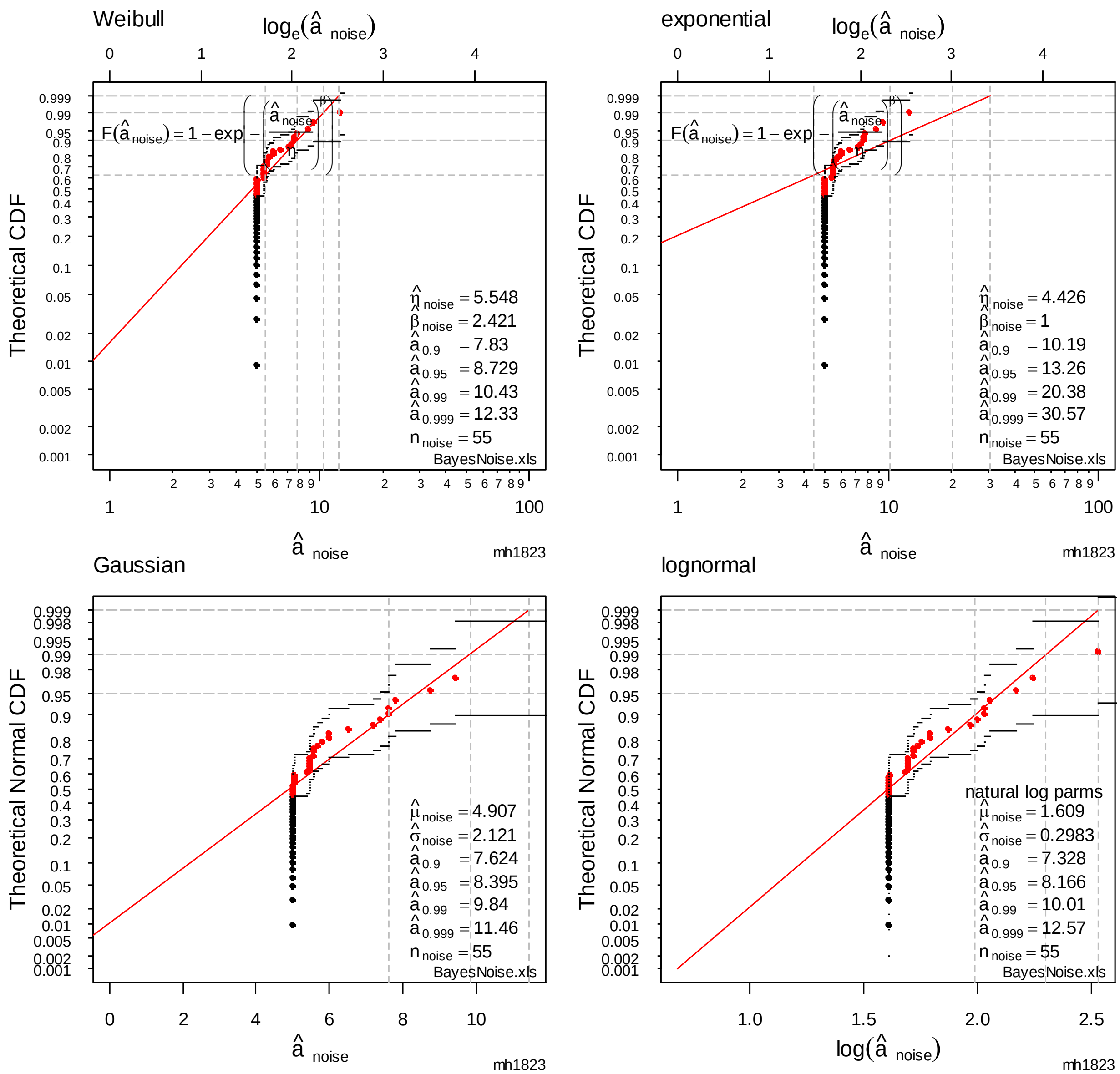


Figure 7. Noise data plotted on four different types of probability ‘paper’

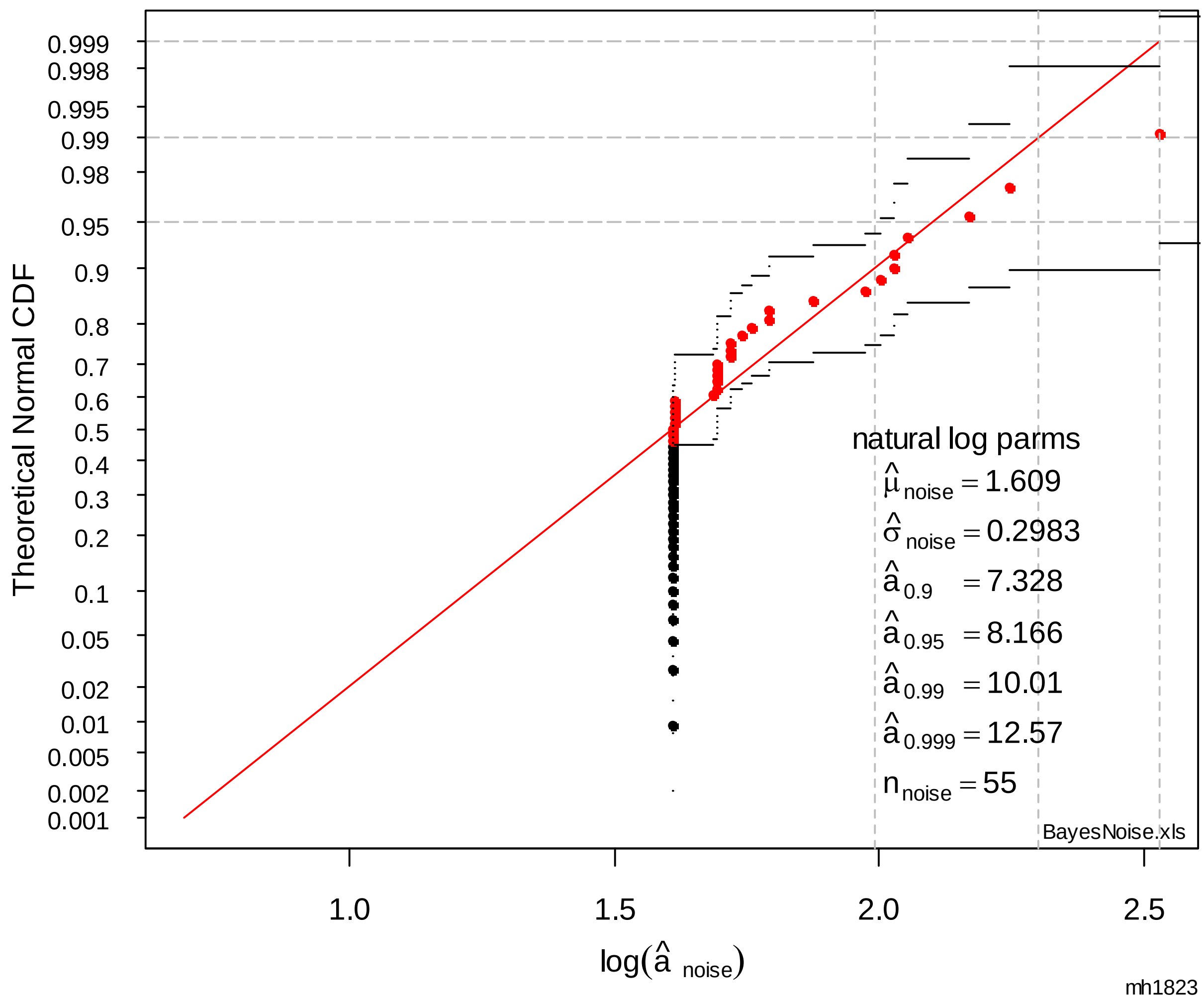


Figure 8. The selected the probability distribution plot for SHM background noise

Figure 9 shows a trade-off plot of getting false positives and $a_{90/95}$ as a function of selected $\hat{a}$ decision. As shown in Figure 9, changing the decision threshold changes both the probability of false positive and the critical target sizes a_{50} (a_{50} is $\hat{a}$ decision), a_{90} and $a_{90/95}$.

Using this plot, three different probability of false positive are considered:

- False alarm rate of .001 corresponds to a threshold: 12.57
- False alarm rate of .01 corresponds to a threshold: 10.01
- False alarm rate of .05 corresponds to a threshold: 8.166

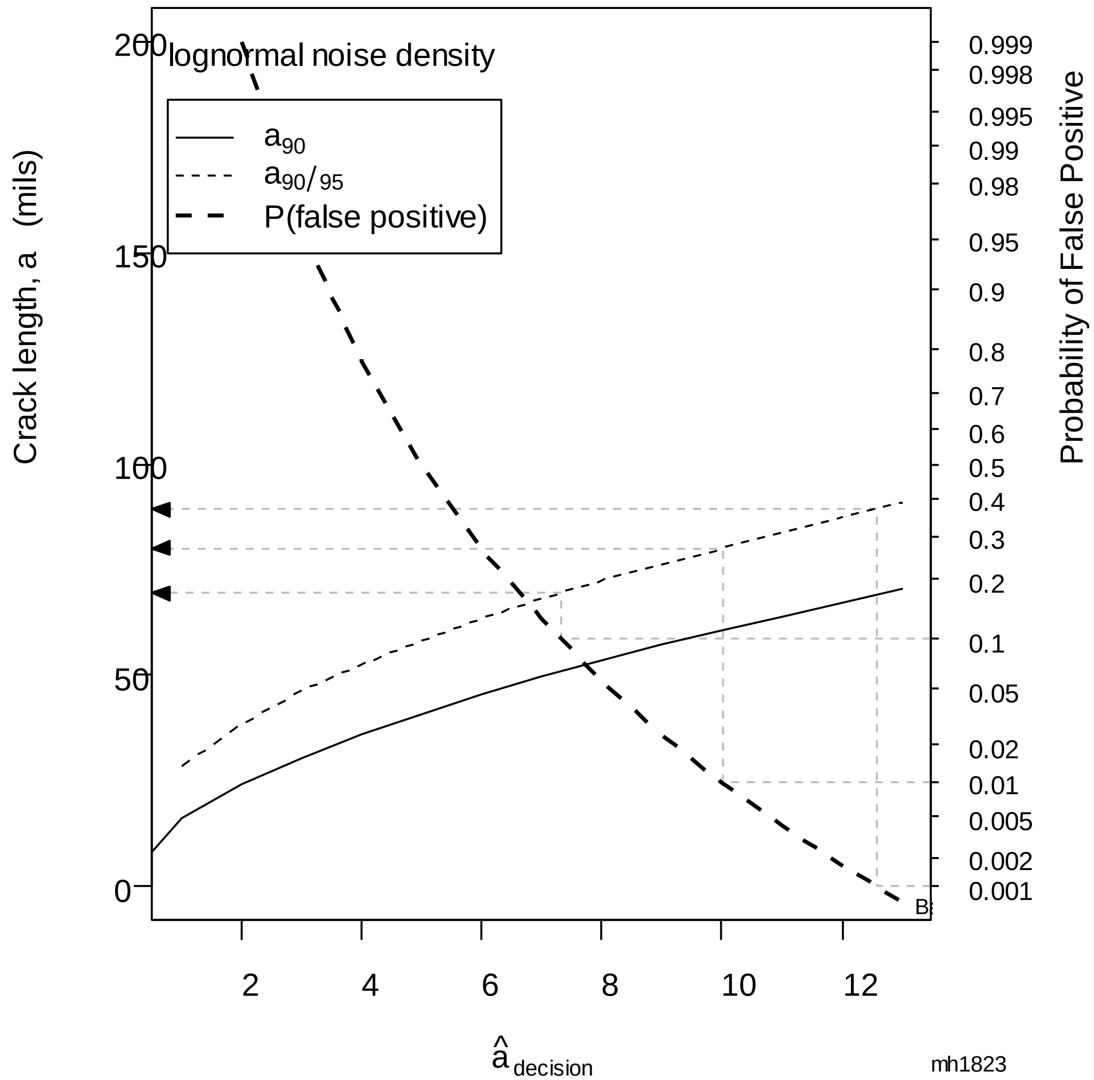


Figure 9. A trade-off plot showing the probability of getting false positives and $a_{90/95}$ as a function of selected $\hat{a}$ decision

Results for False Alarm Rate of .001 (0.1%):

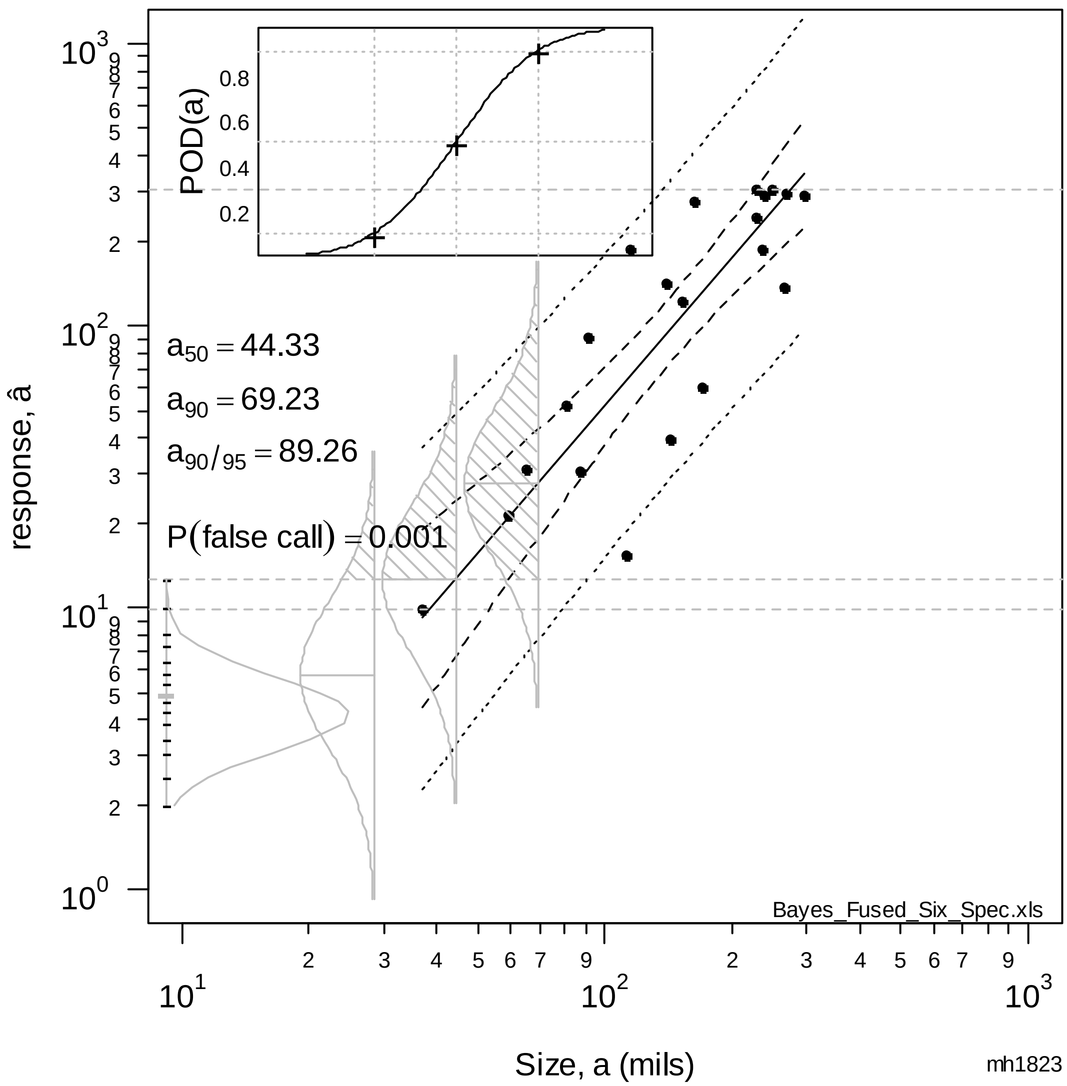


Figure 10. The regression model of Figure 6 superimposed with: a POD curve, the noise distribution, and probability of detection distributions based on prediction scatter placed at various detection points

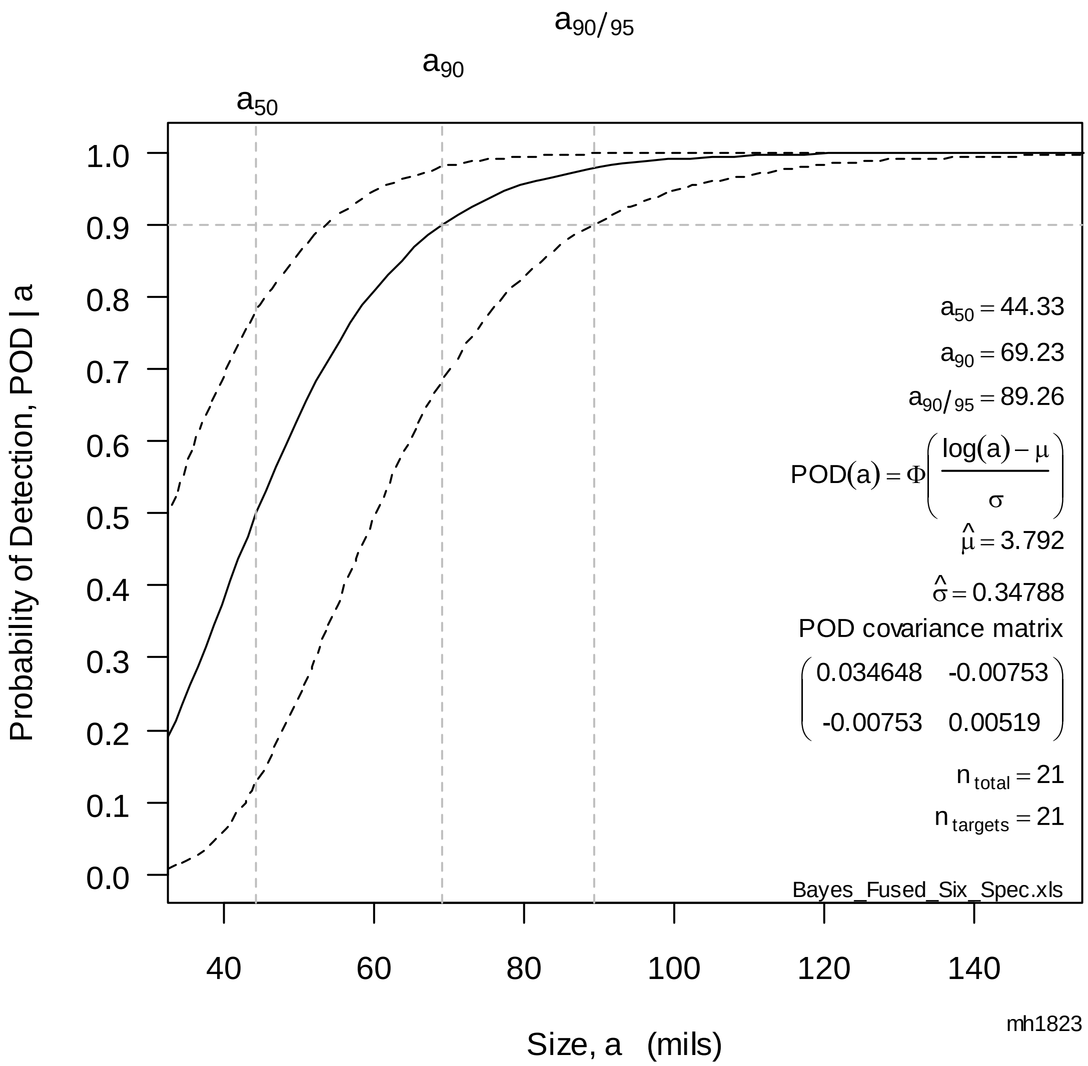


Figure 11. POD Curve for DI data (0.1% *Pr(FA)*)

Results for False Alarm Rate of .01 (1%):

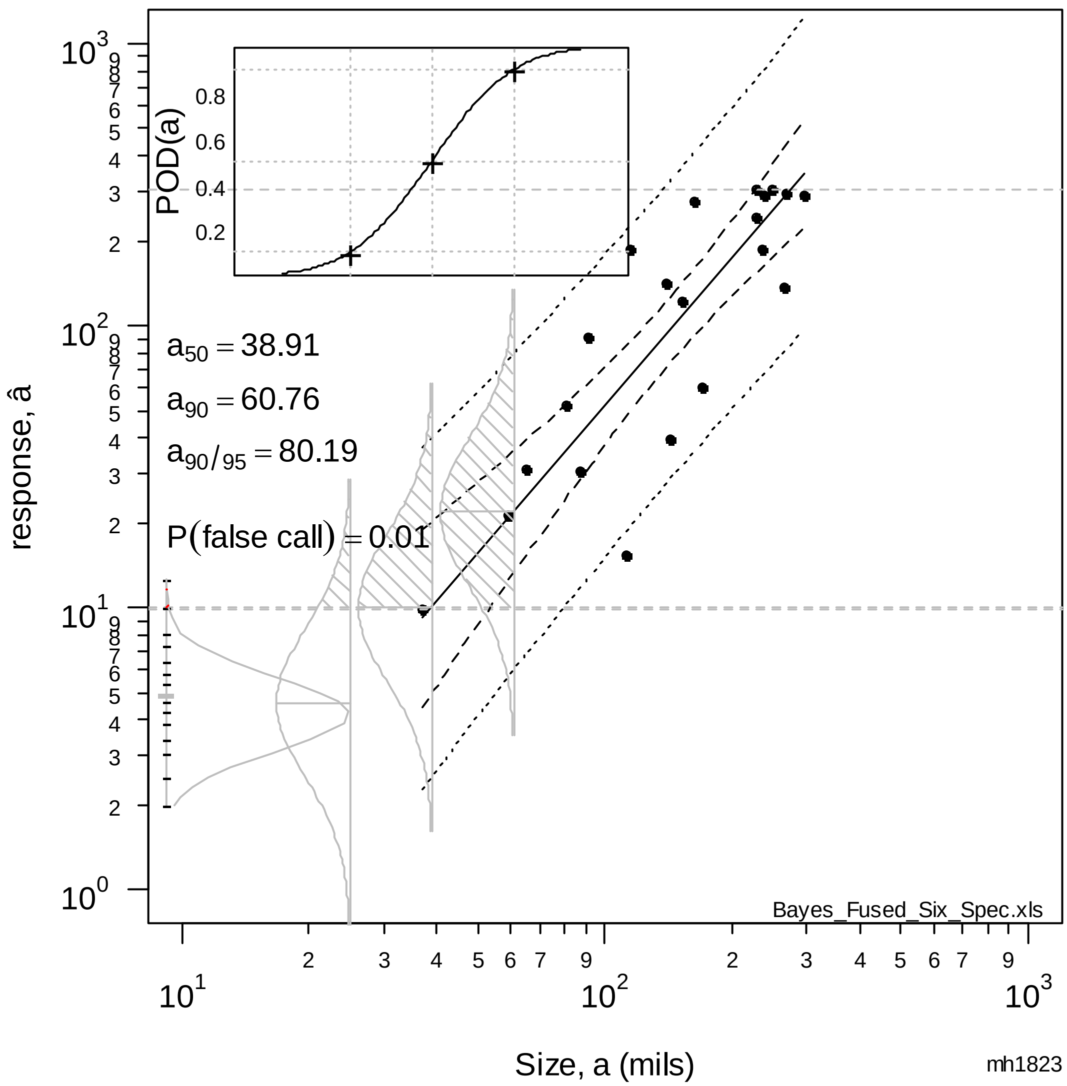


Figure 12. The regression model of Figure 6 superimposed with: a POD curve, the noise distribution, and probability of detection distributions based on prediction scatter placed at various detection points

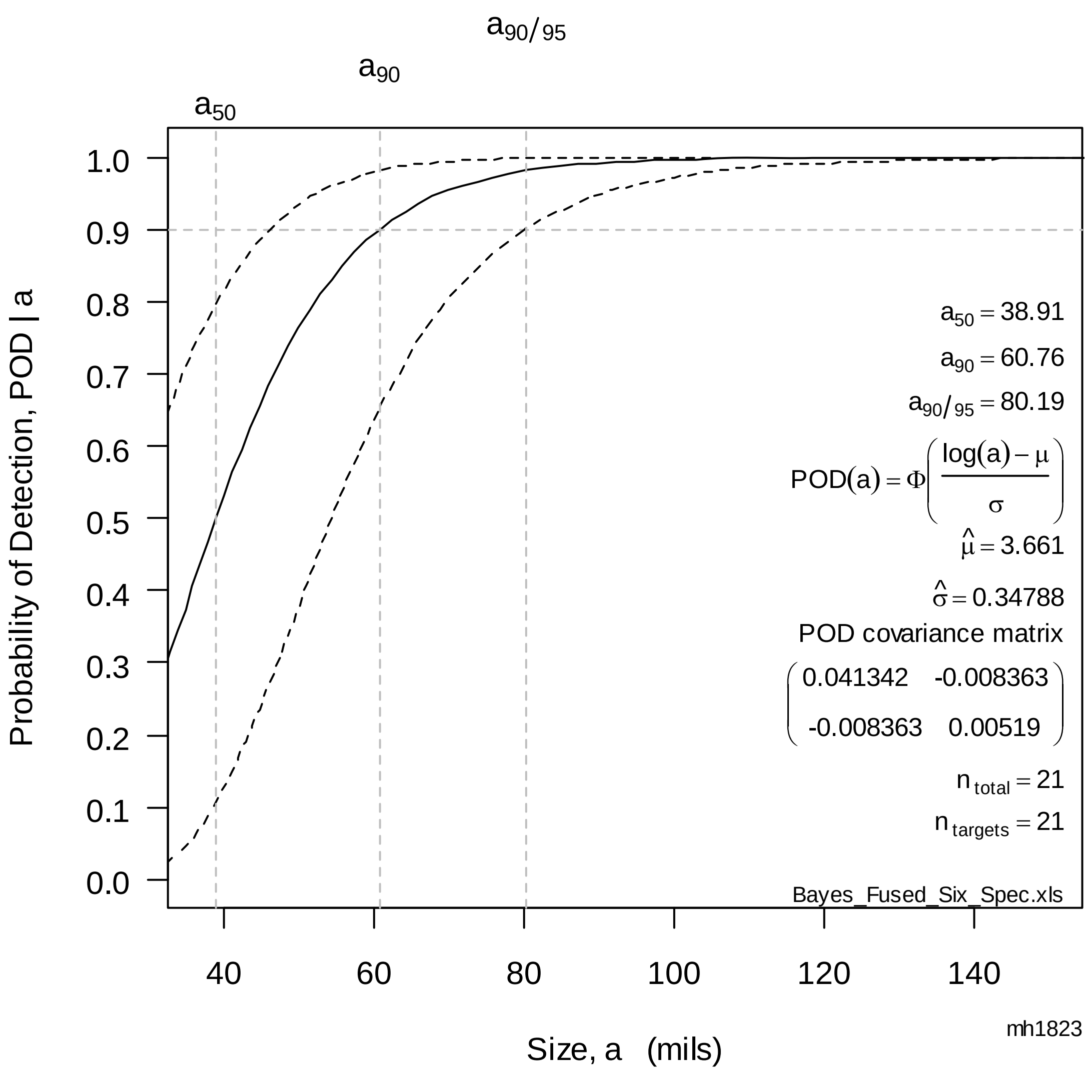


Figure 13. POD Curve for DI data (1% *Pr(FA)*)

Results for False Alarm Rate of .05 (5%):

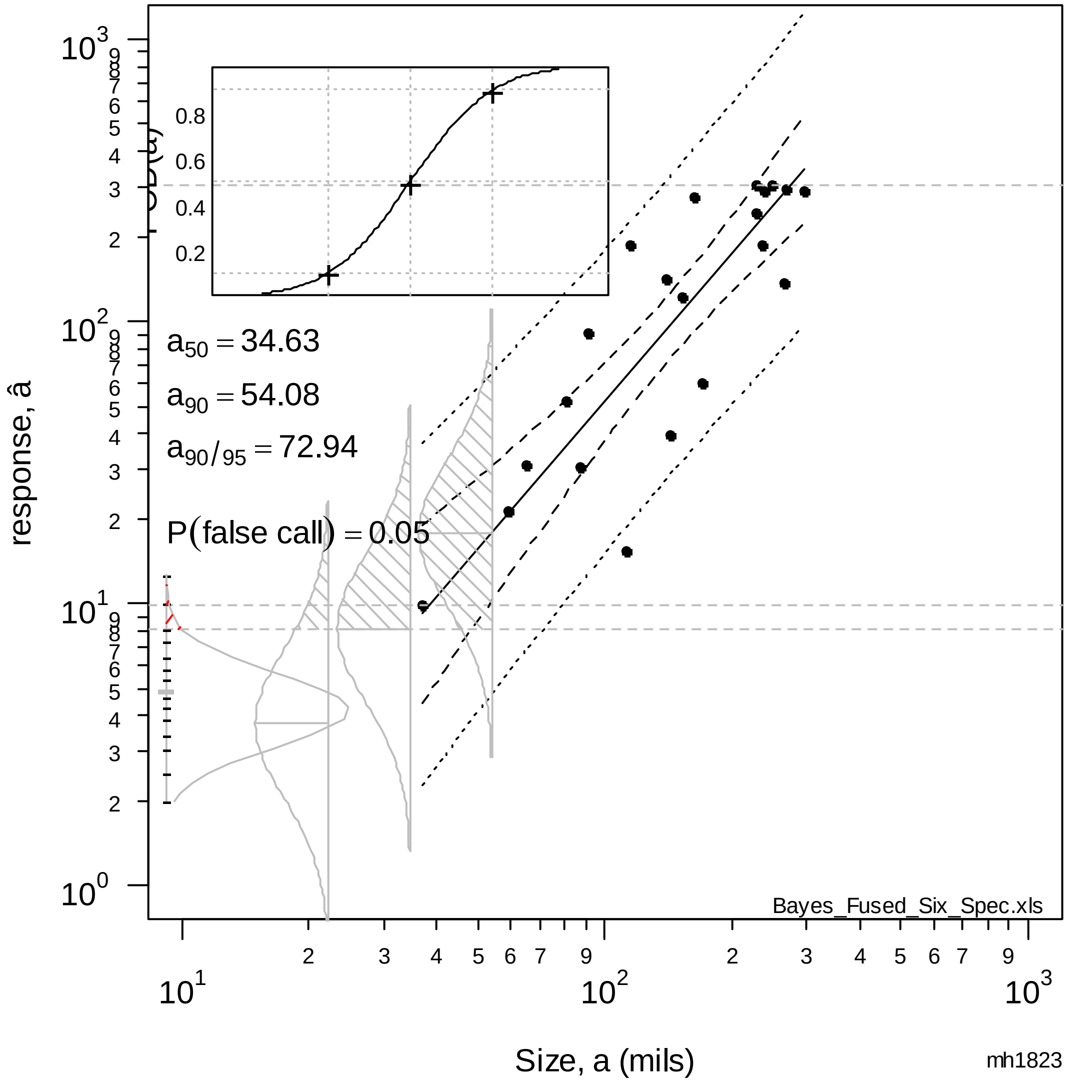


Figure 14. The regression model of Figure 6 superimposed with: a POD curve, the noise distribution, and probability of detection distributions based on prediction scatter placed at various detection points

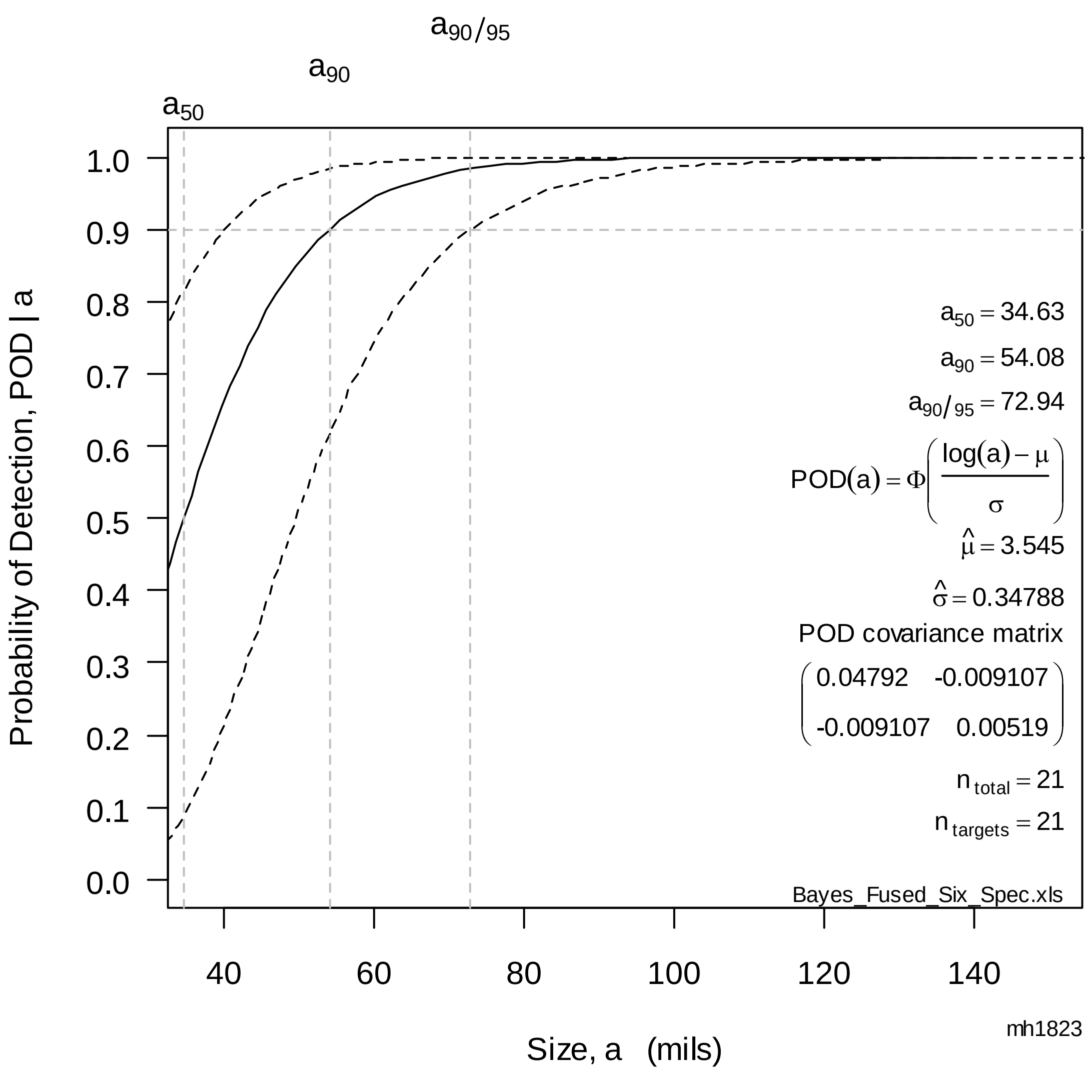


Figure 15. POD Curve for DI data (5% *Pr(FA)*)

Summary of Log - Log Results:

- False alarm rate of .001 corresponds to a threshold: 12.57, $a_{90/95}$ = 89.26
- False alarm rate of .01 corresponds to a threshold: 10.01, $a_{90/95}$ = 80.19
- False alarm rate of .05 corresponds to a threshold: 8.166, $a_{90/95}$ = 72.94

6. Risk Analysis Progress

6.1. RBDMS

6.1.1. Overview of RBDMS

The Reliability-Based Design and Maintenance System (RBDMS) and the PRObability of Fracture (PROF) were developed to estimate the probability of failure for damage tolerant structure. The PROF code was developed by the University of Dayton Research Institute and the RBDMS code was developed by The Boeing Company. Both codes use the same analysis process as shown in Figure 16. With all the input parameters defined, both codes are able to solve and produce the SFPOF and the percentage of crack detected output data for the cost analysis. However, since both codes use different probabilistic analysis strategies and different ways to manage the statistical distributions, their calculated results can differ.

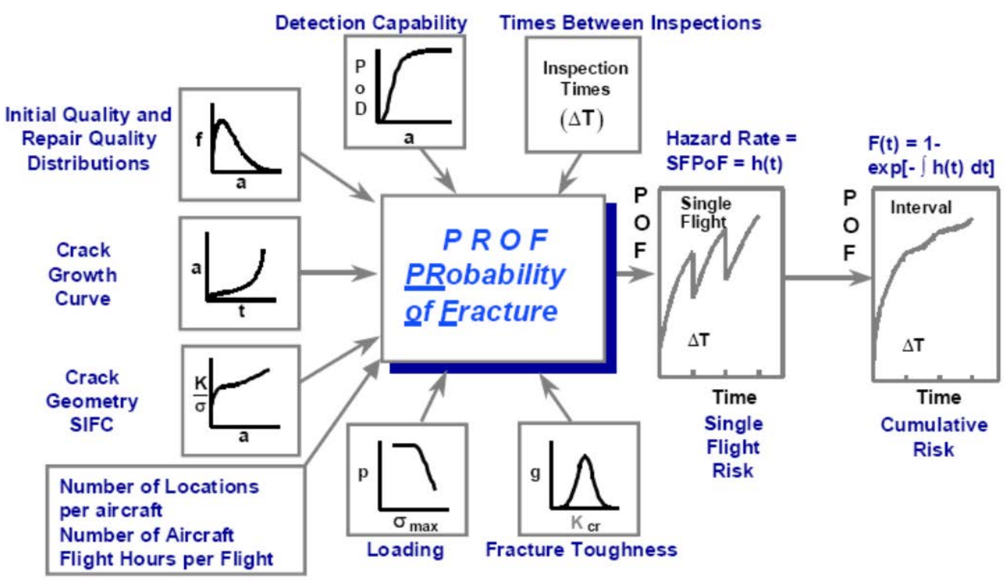


Figure 16: Risk Analysis Input Parameters and Single Flight Probability of Failure (SFPOF)[1]

6.1.2. RBDMS Code Modifications

In the following, the recent RBDMS code modifications are briefly discussed. Details of these modifications can be reviewed in Appendix A.3.

- SFPOF system reliability calculation formula is modified
    - Properly calculates the risk for multiple similar locations
    - Corrected an error which would occur if the EIFS is too large in comparison to the critical crack length (a warning is now issued when this is the case)
- Two inspection types (i.e., multiple PODs) can be used in a single run
- For each inspection the Probability of Crack Detected is subdivided into small, medium, and large crack zones

- The user provides two crack size thresholds to segregate the zones
    - Required by the cost model since larger cracks are more expensive to repair
- Time zero SFPOF calculation has been implemented so that SFPOF plots realistically represent the fact that the initial SFPOF is *non-zero* due to the existence of an initial flaw
- A tabular summary output file is generated for easy import into the cost model
- The output file names have been made more user friendly

6.2. Sixteen Location Subset

6.2.1. Selection

There are several dozen Aircraft C/D wing locations. The data for these were provided by the F-15 Program at a rate of several locations per week. While this information was being prepared it was determined that the analysis should begin on a subset of the full list so that work could begin. Sixteen locations were chosen, including items exhibiting a range of risks. Also, half of the items are easily accessed, and the remainder are inaccessible in the field. As stated in Section 4, items that can be easily accessed at any time are referred to as field-accessible, and locations that can only be accessed at the depot are referred to as depot-accessible.

6.2.2. Brief Description

The locations of the subset are identified below in Table 11. As a measure of the relative risk of each location, the time until the 10^{-7} risk threshold is breached with no inspections is shown. Note there is a large range of risks represented in the subset, with the threshold being breached from a range of 200 to 16,200 FH.

Accessibility	DTA	Description	FH Breach Threshold	Similar Locations
Field	055	Front spar lower flange, XW 169.5	1600	36
	057B	Rear spar lower flange, XW 167.3	3000	32
	164	Lower wing skin at rear spar, XW 79	5300	154
	165	Lower wing skin at shoulder rib & intermediate spar, fastener hole	5900	32
	166B	Lower wing skin at shoulder rib and intermediate spar, bend radius	16200	2
	184	Lower fwd wing skin at XW 188	1100	48
	187	Lower forward wing skin surface cracks at front spar	700	134
	188	Lower aft wing skin at main spar, XW 163.6	600	20
Depot	097	Intermediate spar seal groove at lower lug backup	9800	2
	115	Aft lower skin	200	95
	124B	Front spar lower flange at XW 224.8	3800	12
	134B	T.E. closure spar – upper flange	1200	8
	138B	T.E. closure spar xw 224	1200	4
	143	Wing fairing side panel rib cap	1800	2
	144	Inboard T.E. rib at XW 108.83	700	2
	203	Front spar tooling hole at XW 216	7600	2

Table 11. Description of the Sixteen Location Subset

6.3. Inspection Scenarios for Each DTA

As indicated in Section 4.6, there are several inspection scenarios to consider for each DTA item. These are further described as follows:

- Baseline
  - NDE inspections only
  - Inspection times determined by traditional deterministic damage tolerance with rule-of-thumb knockdown factors
- Risk-based
  - NDE inspections only
  - Inspection times determined by component-level SFPOF threshold of 10^{-7}
- In-situ
  - Locations without in-situ sensors
    - Results correspond to the risk-based NDE scenario for these items
  - Field-accessible locations with in-situ sensors
    - No penalty for crack detections made in the field
    - Single in-situ POD curve used over the life of the platform
  - Depot-accessible locations with in-situ sensors
    - 500 man hour penalty and 8 hour downtime penalty for repairs made in the field
    - Field POD curve may be of low fidelity
    - Depot POD curve may be of high fidelity

6.3.1. Baseline Inspection Times

The first step in performing the risk analysis for the baseline case is the determination of the inspection times that are used in the field. Note that the determination of baseline times differs between field-accessible and depot-accessible locations, as NDE inspections can only occur for depot-accessible locations at multiples of 1800 FH. That is, PDM occurs only at flight hours 1800, 3600, 5200, 7200, 9000, 10800, 12600, 14400, 16200, and 18000, so depot-accessible locations can only be inspected at these times. Several characteristic example calculations are shown in this section.

6.3.1.1.1. Field-Accessible Location: DTA 166B

The relevant parameters for determining the baseline inspection times follow. These parameters were obtained from the F-15 Program.

- Safety Limit
  - The life predicted by the deterministic damage tolerance analysis
- DI
  - Multiplied by the safety limit to determine the first inspection time
- ΔDI
  - Multiplied by the safety limit to determine the subsequent inspection times

For DTA 166B, the safety limit, DI, and ΔDI are 3500 FH, 0.5, and 0.5, respectively. Note that the DI and ΔDI are not necessarily equal in general.

Recall that NDE inspections in this analysis will only occur at multiples of 200 FH. To more accurately represent what is done in the field, the inspection times up to 18,000 FH are first calculated and then the times are rounded to the nearest 200 FH multiple. Note that the final inspection time was always cut off at 18,000 FH. See Table 12 below.

Inspection #	1	2	3	4	5	6	7	8	9	10	11
Interval Time	1750	1750	1750	1750	1750	1750	1750	1750	1750	1750	1750
Cumulative Time	1750	3500	5250	7000	8750	10500	12250	14000	15750	17500	19250
Baseline Inspection Times	1800	3600	5200	7000	8800	10600	12200	14000	15800	17600	18000

Table 12. DTA 166B Baseline Inspection Times

6.3.1.1.2. Depot-Accessible Location: DTA097

Depot-accessible locations can only be inspected at PDM. The maintenance plan occasionally specifies a safety limit, DI, and ΔDI as in the case of field-accessible locations. The times are calculated in similar fashion. However, rounding is somewhat different. The inspection time is rounded to the earlier 1800 FH multiple, unless it is within 400 FH of the next 1800 FH multiple. As an example DTA 097 is calculated as follows. The safety limit, DI, and ΔDI are 9000 FH, 0.5, and 0.5, respectively. See Table 13 below.

Note that for a location such as this, it is possible to perform NDE inspections more often if desired, since there are currently PDMs at which this location is not inspected.

Inspection #	1	2	3	4
Interval Time	4500	4500	4500	4500
Cumulative Time	4500	9000	13500	18000
Baseline Inspection Times	3600	9000	12600	18000

Table 13. DTA 097 Baseline Inspection Times

6.3.1.1.3. Depot-Accessible Location: DTA124B

When the maintenance plan for a depot-accessible location does not indicate a value for DI, and ΔDI, it instead calls for inspection at *every PDM*. For these locations, the baseline inspection times are simply the multiples of 1800 up to 18000 FH, or: 1800, 3600, 5200, 7200, 9000, 10800, 12600, 14400, 16200, and 18000. This is the case for DTA 124B.

Note that for each of these locations, performing more NDE inspections is not possible. The location is already inspected at every PDM. Thus the risk-based scenario is equivalent to the baseline scenario.

6.3.2. Risk-Based Inspection Times

For convenience the risk-based maintenance strategy is referred to as the Risk strategy. In this scenario, the inspection times are determined by the RBDMS results. Each inspection is scheduled at the 200 FH multiple nearest the flight hour where the SFPOF of a location reaches the 10^{-7} threshold, allowing for slight exceedance at this stage of the analysis. Several characteristic examples are shown here.

The SFPOF plots for the baseline and risk scenarios for DTA 166B (field-accessible) are shown in Figure 17. In this case, the baseline is very conservative. In the risk scenario only two inspections are required to keep the SFPOF below the 10^{-7} threshold, whereas the baseline scenario includes eleven inspections (the first several inspections do not alter the SFPOF as the risk is too low to see on the plot).

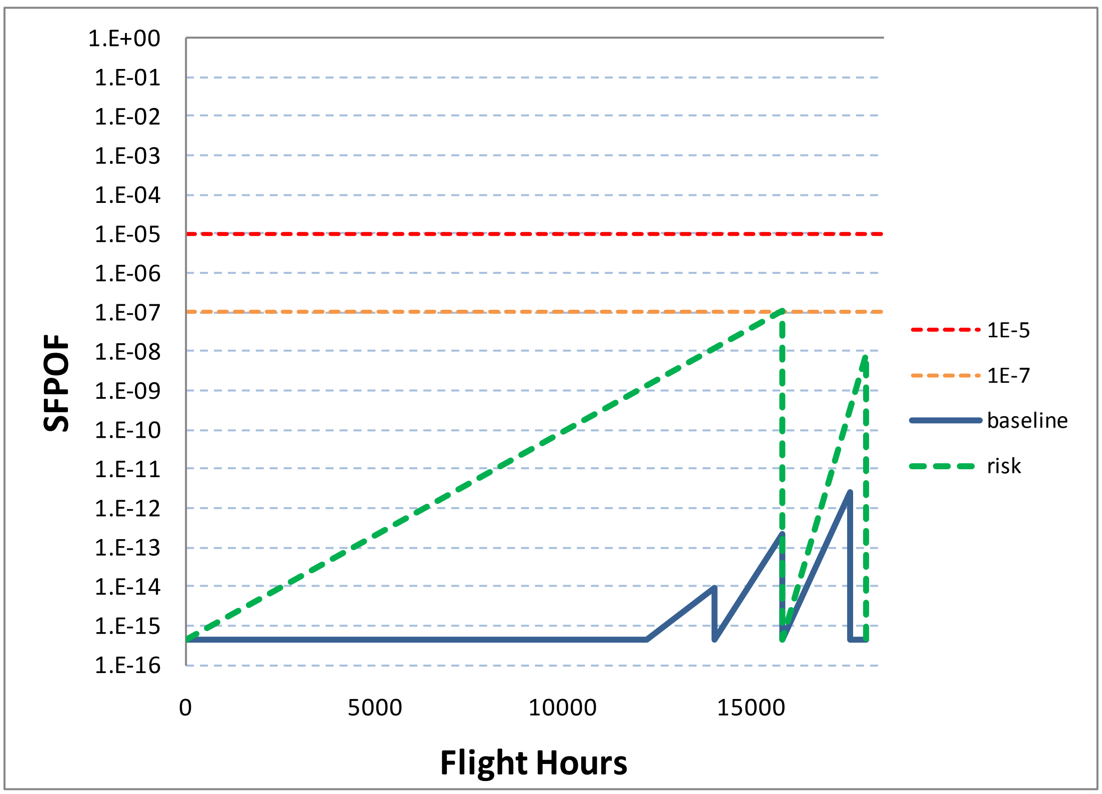


Figure 17. DTA 166B SFPOF Plots for the Baseline and Risk Scenarios

The SFPOF plot for the baseline scenario of the depot-accessible location DTA 124B is shown below in Figure 18. Recall that in the baseline scenario there is an NDE inspection at every PDM. There is no risk scenario for this location due to the fact that the risk exceeds the threshold when the location is inspected at every opportunity. For this location, the only options for reducing the risk to an acceptable level are to re-design the part or to utilize in-situ sensors to inspect the location more often. This is explored in the next section.

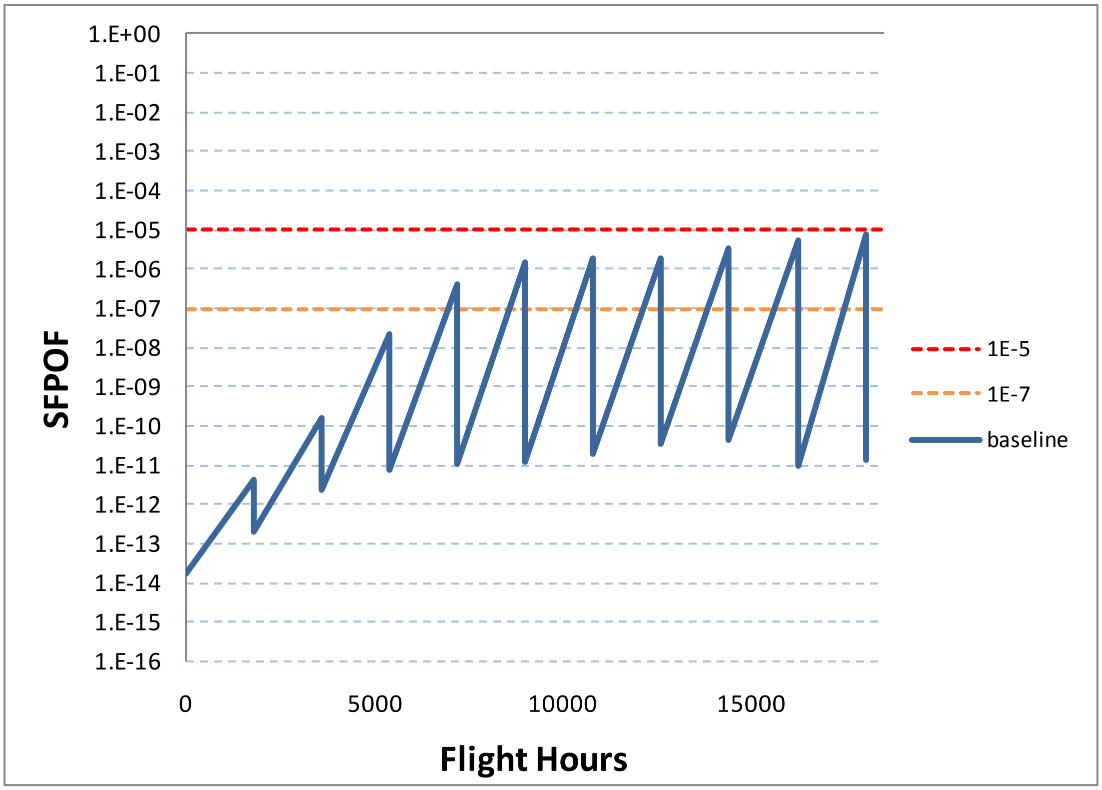


Figure 18. DTA 124B SFPOF Plot for the Baseline Scenario

In Figure 19 below are the SFPOF plots for DTA 055 (field-accessible). Note that the risk of the baseline scenario, with only six inspections, is excessively high. This high risk issue is discussed in Section 6.5. For this location, 34 NDE inspections – with a correspondingly high number of man-hours – are required over the life to remain beneath the risk threshold. Hence this location is an excellent candidate for in-situ sensors.

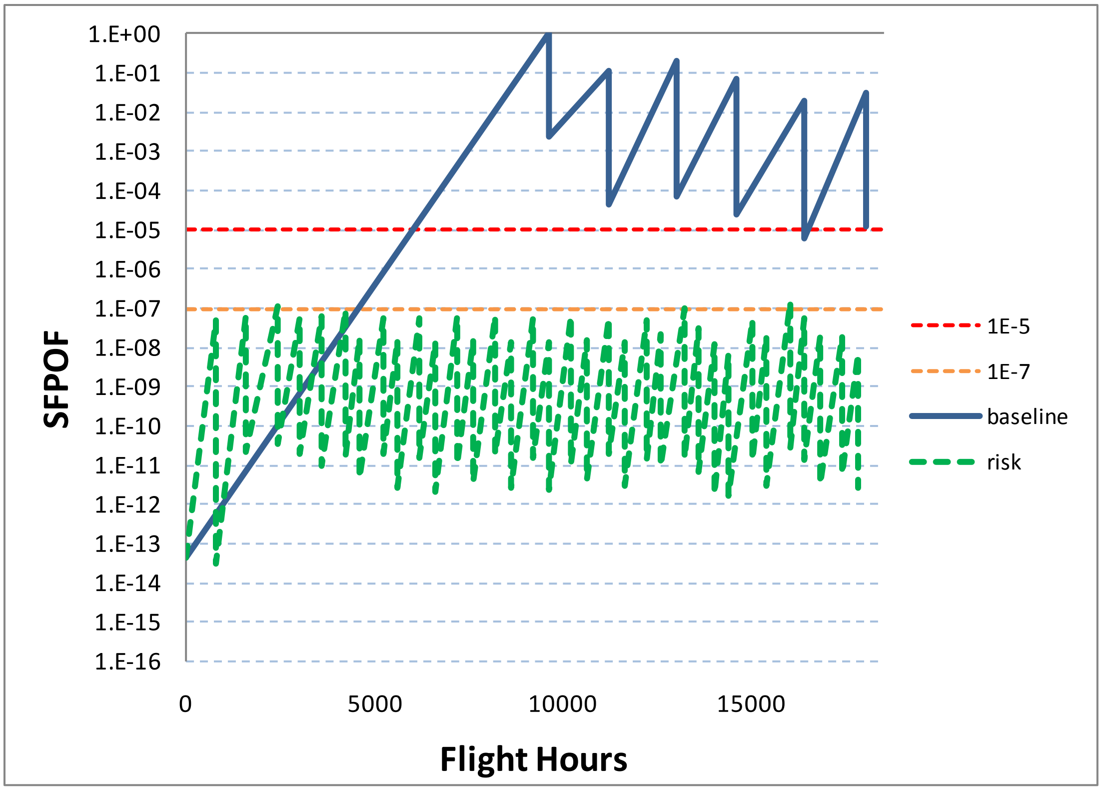


Figure 19. DTA 055 SFPOF Plots for the Baseline and Risk Scenarios

6.3.3. In-Situ Inspection Times

As stated previously, the in-situ scenarios will have constant inspection intervals of either 300 or 600 FH depending on the location. If the 600 FH interval will suffice, it is preferable to the 300 FH interval due to the fact that half as many false calls are expected to occur over the life (this is particularly relevant if the POD curve being used is of the medium or high fidelity variety). Several examples of the selection of POD capability and inspection frequency are shown here, DTA 184 (field-accessible), DTA 164 (field-accessible) and DTA 138B (depot-accessible). Recall the list of acronyms for the strategies under consideration as shown in Table 6 on page 17.

An inspection interval of 600 FH cannot be used for DTA 184 because the risk exceeds the threshold at several points. SFPOF plots are shown in Figure 20 with inspections at 300 FH intervals utilizing the medium and low fidelity POD curves. The risk of each of these strategies is similar; therefore both are retained as potential strategies. The high fidelity POD curve is not considered unless it is absolutely required to maintain the risk at acceptable levels, as the false call rate is relatively high.

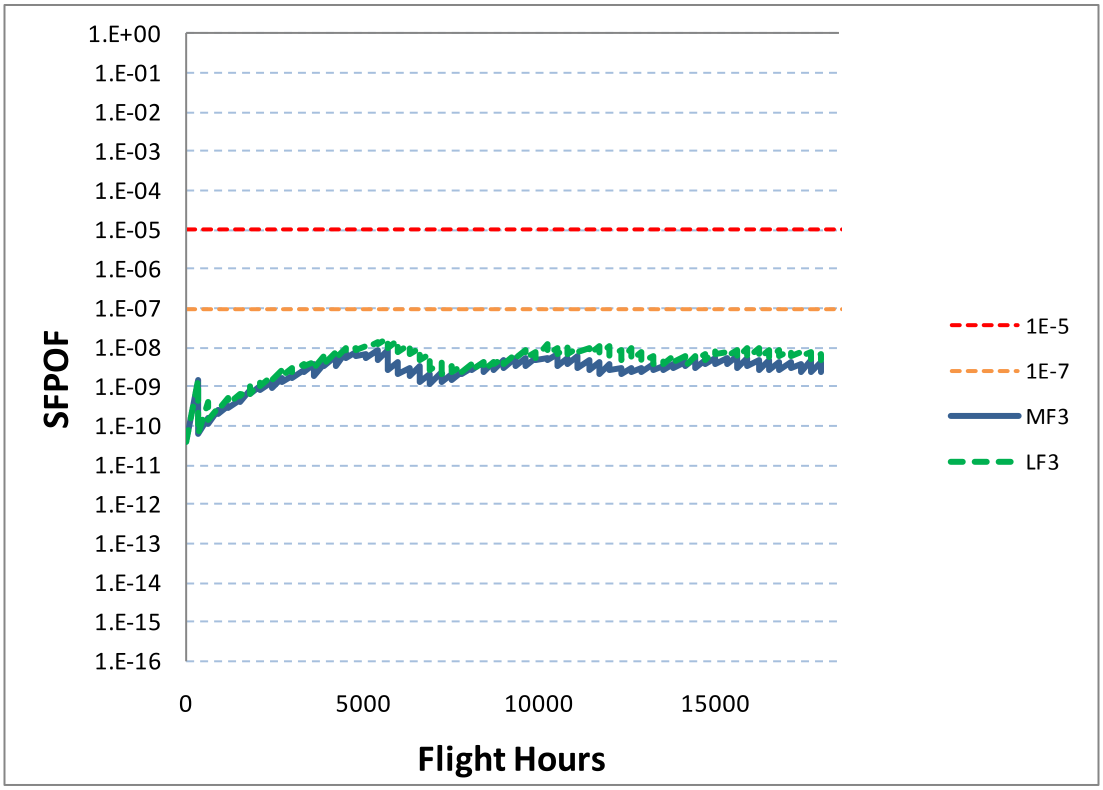


Figure 20. DTA 184 SFPOF Plots for the In-situ Scenario

In Figure 21, the SFPOF of DTA 164 using the low fidelity POD for both 300 and 600 FH intervals are shown (LF3 and LF6). The low fidelity POD corresponds to a false call rate of 0.001% per inspection. The lesser fidelity POD curve is used for this field-accessible location because DTA 164 includes 154 similar locations and the small crack repair time for this location is 60 man-hours, thus the penalty for a false alarm is a concern as the consequence for a false alarm is an unnecessary small crack repair. For this location, the interval of 600 FH may be more appropriate as the risk is adequately controlled and increasing the inspection frequency to every 300 FH will double the false call rate. However, the choice between these two options cannot be made with the risk analysis alone. The increased risk of the 600 FH intervals may result in a higher cost due to the increased chance of finding large cracks at later inspections. Hence both of these options must be analyzed using the cost model to determine the optimal choice, and both are included in the grid shown in Table 7.

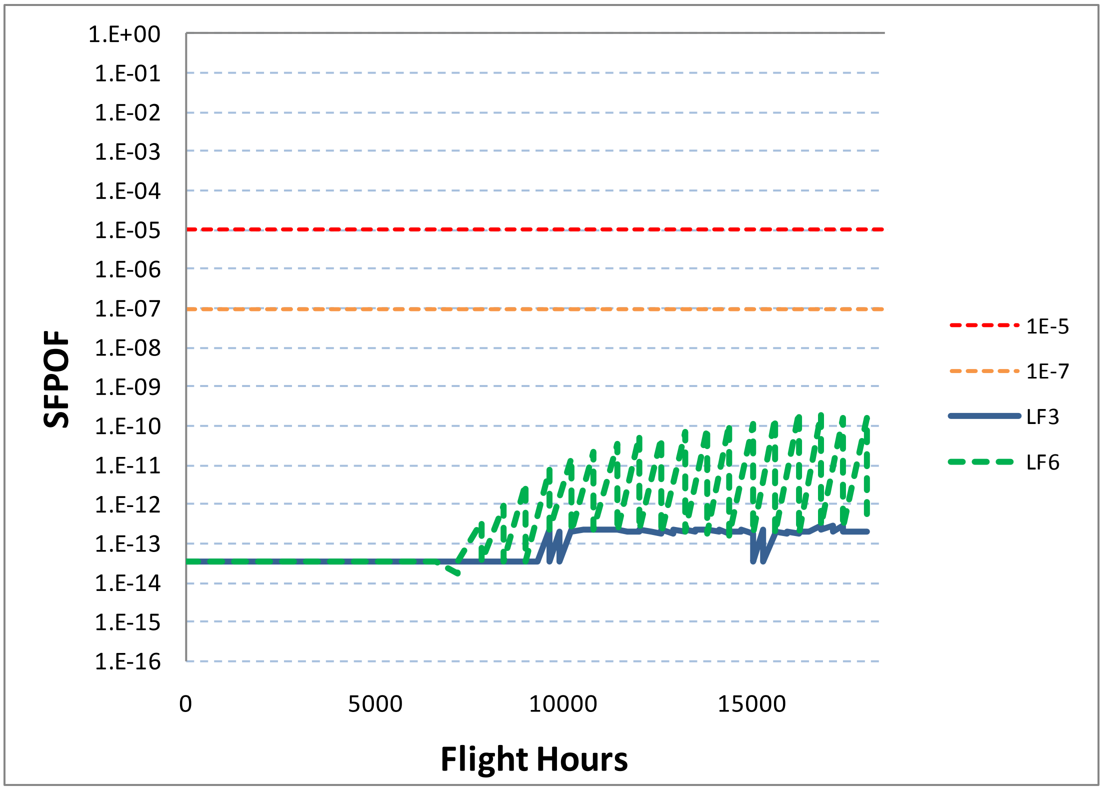


Figure 21. DTA 164 SFPOF Plot for the In-situ Scenario

Figure 22 displays the Probability of Crack Detection (PCD) of medium and large size at each inspection for DTA 164. With 600 FH inspection intervals, the chance of finding medium cracks is increased, and there is now a chance that large cracks will be found later on in the life. The repair times for medium and large cracks are 60 and 240 man-hours, respectively. In addition, if a large crack is found there is a $100,000 part replacement cost. Hence it is possible that the chance of finding larger cracks will outweigh the costs associated with false calls. It is not possible to choose the optimal strategy based on the risk analysis alone. The cost model is required to make the optimal selection; therefore both options are retained for consideration.

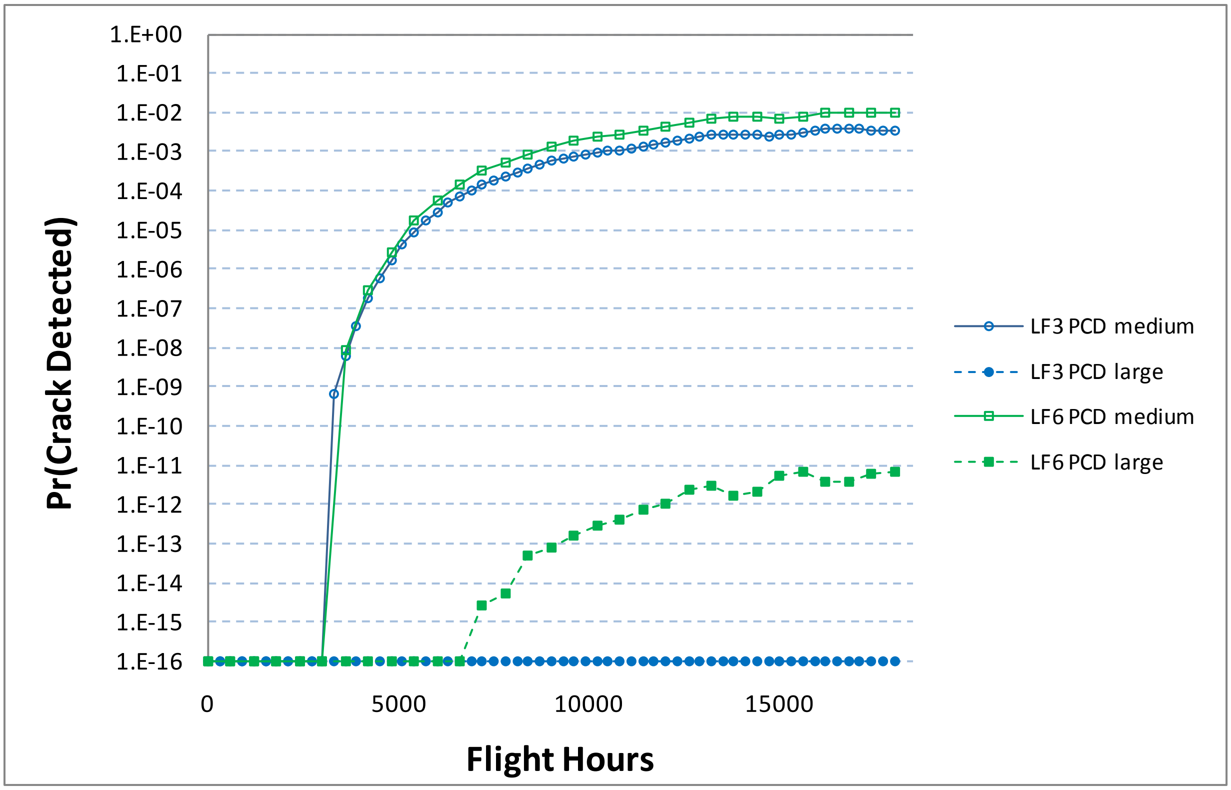


Figure 22. Probability of Detecting Cracks of Medium and Large Size, DTA 164

Each of the DTA items discussed above are field-accessible, therefore only one POD curve is used over the life of the platform. For depot-accessible locations, it may be preferable to use a high fidelity POD curve when the aircraft is at the depot so that as many cracks as possible are found at these times. When away from the depot, a lesser fidelity POD curve is used to limit crack detections and therefore limit the number of times the wing will need to be detached and shipped to the depot for repairs, thus incurring large penalties in the cost model.

This scenario is examined here for DTA 138B, a depot-accessible location. Figure 23 is a combined plot of the SFPOF and the PCD of large cracks for this location with strategy LF3 throughout the life. Recall, the low fidelity POD is used because there are significant cost penalties for depot-accessible DTA items when cracks are detected away from the depot. The risk is maintained at the threshold using this POD; however, the in-situ inspections which occur at the depot possess unnecessarily low capability as the penalties do not apply for these inspections.

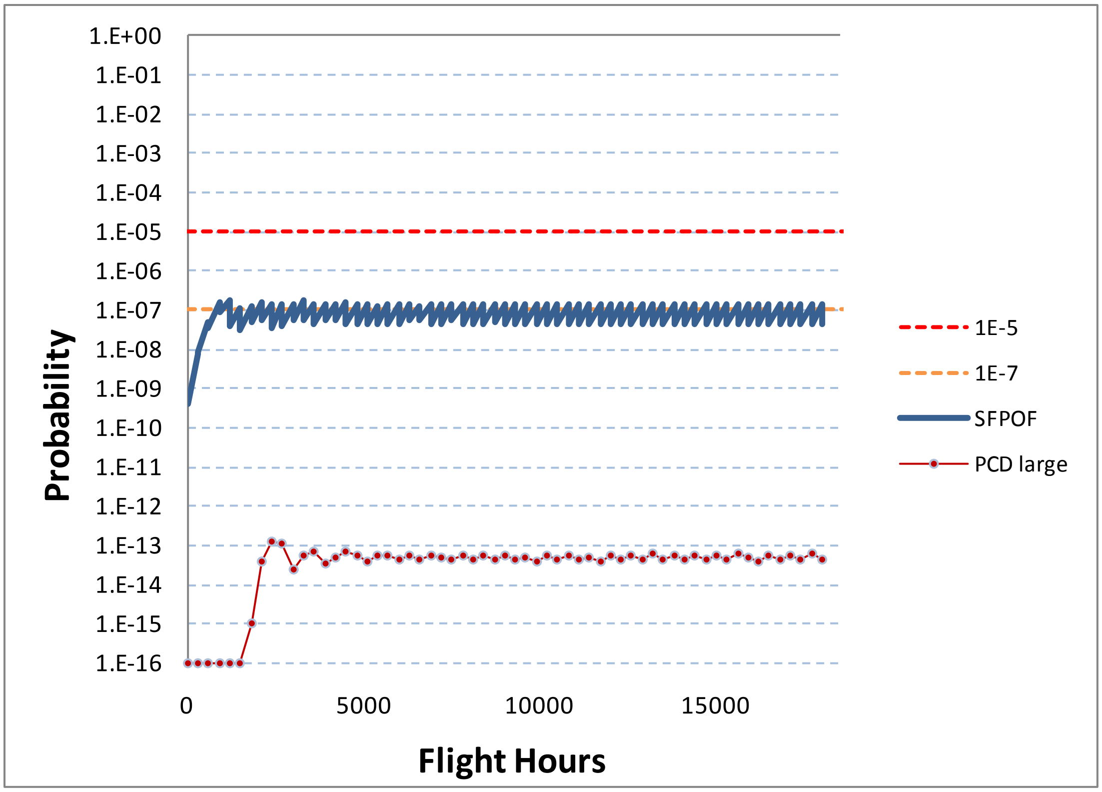


Figure 23. DTA 138B Combined SFPOF and PCD Plot with Low Fidelity POD

In Figure 24 below, the capability of the in-situ sensors differs between the depot and the field. The strategy used is MixHL3. That is, in the depot, the high fidelity POD with Pr(FA) = 1% is used with the hope of finding all cracks before the plane is sent out into the field. In the field, the low fidelity POD with Pr(FA) = 0.001% is used with the intention of only discovering larger cracks. Note that the chance of discovering large cracks has been significantly reduced in general without much change in the SFPOF. The other options for this DTA item are not shown. This strategy appears to be superior to the others, therefore it is the only in-situ strategy retained in the grid of Table 7.

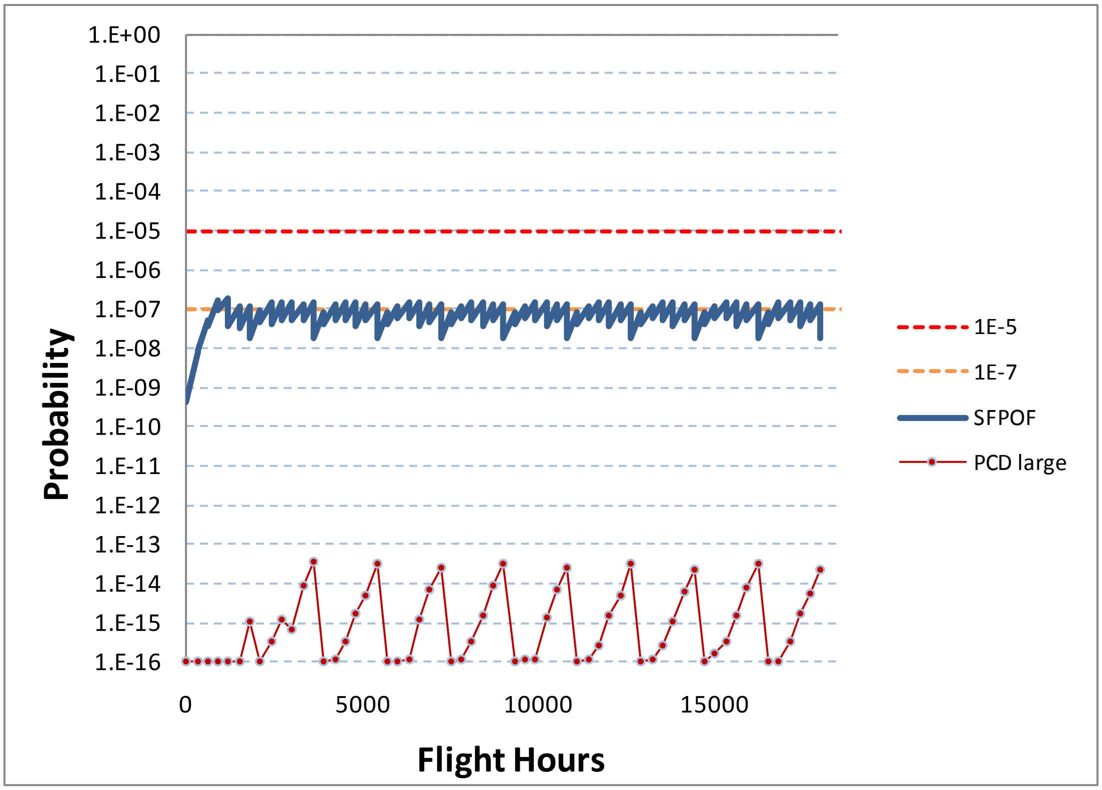


Figure 24. DTA 138B Combined SFPOF and PCD Plot with Differentiated Fidelity POD

6.4. RBDMS Results Summary

The complete details of every risk analysis included for consideration in the system are not shown in this document. A summary of these risk runs is shown below in Table 14. Descriptions for the columns precede the table. Note that when implementing the Risk strategy for this preliminary analysis the 10^{-7} threshold was aimed for, hence many of the risk-based SFPOF numbers are very close to 10^{-7} (e.g. $1.05*10^{-7}$). The column which counts those risks over the threshold used $2*10^{-7}$ instead so as not to count these borderline cases.

- Maximum SFPOF
  - The highest SFPOF at any time
- Median SFPOF
  - The median value of SFPOF *before* inspections (the peaks only)
- Maximum Large PCD
  - The maximum of the probabilities of detecting a large crack at inspection
- Number Insp's
  - The number of inspections that take place over the 18,000 flight hour life
- Number > $2*10^{-7}$
  - The number of inspections at which the SFPOF is greater than $2*10^{-7}$
- Number > 10^{-5}
  - The number of inspections at which the SFPOF is greater than 10^{-5}

DTA	Strategy	Maximum SFPOF	Median SFPOF	Maximum Large PCD	Number Insp's	Number > 2E-7	Number > 1E-5
dta055	Base	1.0E+00	7.2E-02	1.5E-03	6	6	6
	LF3	2.8E-12	5.7E-13	0.0E+00	60	0	0
	Risk	1.4E-07	4.8E-08	9.8E-10	34	0	0
dta057B	Base	1.0E+00	5.0E-01	2.0E-01	2	2	2
	LF6	1.2E-13	6.0E-14	0.0E+00	30	0	0
	Risk	1.1E-07	6.4E-08	6.7E-09	16	0	0
dta097	Base	3.1E-15	3.1E-15	1.0E+00	5	0	0
	Risk	2.7E-08	1.7E-08	1.0E+00	2	0	0
dta115	Base	9.5E-01	6.0E-01	0.0E+00	10	10	10
	MixHL3	6.7E-03	9.0E-04	0.0E+00	60	60	60
dta124B	Base	7.4E-06	1.5E-06	8.6E-04	10	7	0
	LF6	7.5E-11	1.1E-11	5.6E-12	30	0	0
dta134B	Base	4.2E-04	3.1E-04	2.6E-01	10	10	10
	MF3	7.6E-07	2.5E-07	3.8E-09	60	48	0
	MixHL3	2.8E-06	5.5E-07	9.1E-08	60	49	0
dta138B	Base	2.1E-03	8.9E-04	9.4E-04	10	10	9
	MixHL3	1.9E-07	1.3E-07	1.9E-15	60	0	0
dta143	Base	2.3E-04	1.2E-04	5.7E-03	10	9	9
	LF6	7.9E-14	3.3E-14	3.2E-06	30	0	0
	MixML6	1.5E-14	8.4E-15	6.1E-07	30	0	0
dta144	Base	5.4E-02	1.7E-02	6.6E-03	10	10	10
	MF3	3.4E-07	7.6E-08	2.2E-12	60	4	0
	MixHL3	1.0E-06	1.9E-07	2.3E-10	60	29	0
dta164	Base	1.0E+00	5.7E-05	9.1E-07	5	5	4
	LF3	2.9E-13	3.4E-14	0.0E+00	60	0	0
	LF6	2.1E-10	3.4E-12	7.5E-14	30	0	0
	Risk	1.1E-07	5.2E-08	1.1E-09	20	0	0
dta165	Base	7.3E-01	8.4E-05	4.9E-06	8	8	7
	LF3	2.1E-13	4.6E-14	0.0E+00	60	0	0
	LF6	5.8E-08	4.5E-09	9.6E-10	30	0	0
	Risk	8.9E-08	2.9E-08	4.4E-09	26	0	0
dta166B	Base	2.6E-12	4.4E-16	0.0E+00	11	0	0
	Risk	1.1E-07	8.5E-09	2.8E-08	2	0	0
dta184	Base	3.9E-05	7.3E-08	1.1E-09	30	1	1
	LF3	1.7E-08	7.4E-09	2.5E-13	60	0	0
	MF3	8.7E-09	4.0E-09	3.0E-14	60	0	0
	Risk	1.3E-07	7.7E-08	1.2E-09	31	0	0
dta187	Base	9.2E-04	6.1E-08	0.0E+00	30	2	1
	LF3	2.3E-08	2.7E-09	0.0E+00	60	0	0
	MF3	2.3E-08	1.5E-10	0.0E+00	60	0	0
	Risk	1.9E-07	5.8E-08	0.0E+00	31	0	0
dta188	Base	1.4E-03	1.1E-04	5.5E-06	4	4	4
	LF6	1.9E-11	6.2E-12	1.5E-16	30	0	0
	Risk	1.2E-07	1.0E-07	5.4E-09	9	0	0
dta203	Base	5.2E-12	2.3E-12	5.4E-07	10	0	0
	Risk	8.5E-09	5.1E-09	1.3E-02	3	0	0

Table 14. RBDMS Results Summary

Several locations in this table have very high risk and exceed the threshold repeatedly. This issue is discussed in the next subsection.

6.5. High Risk Locations

The SFPOF of several locations in the sixteen location subset is excessively high. Some of these were shown earlier in this section. An additional example, DTA 115, is shown in Figure 25 below. The MixHL3 is the best strategy; hence it is used in this preliminary analysis. However, it is not acceptable.

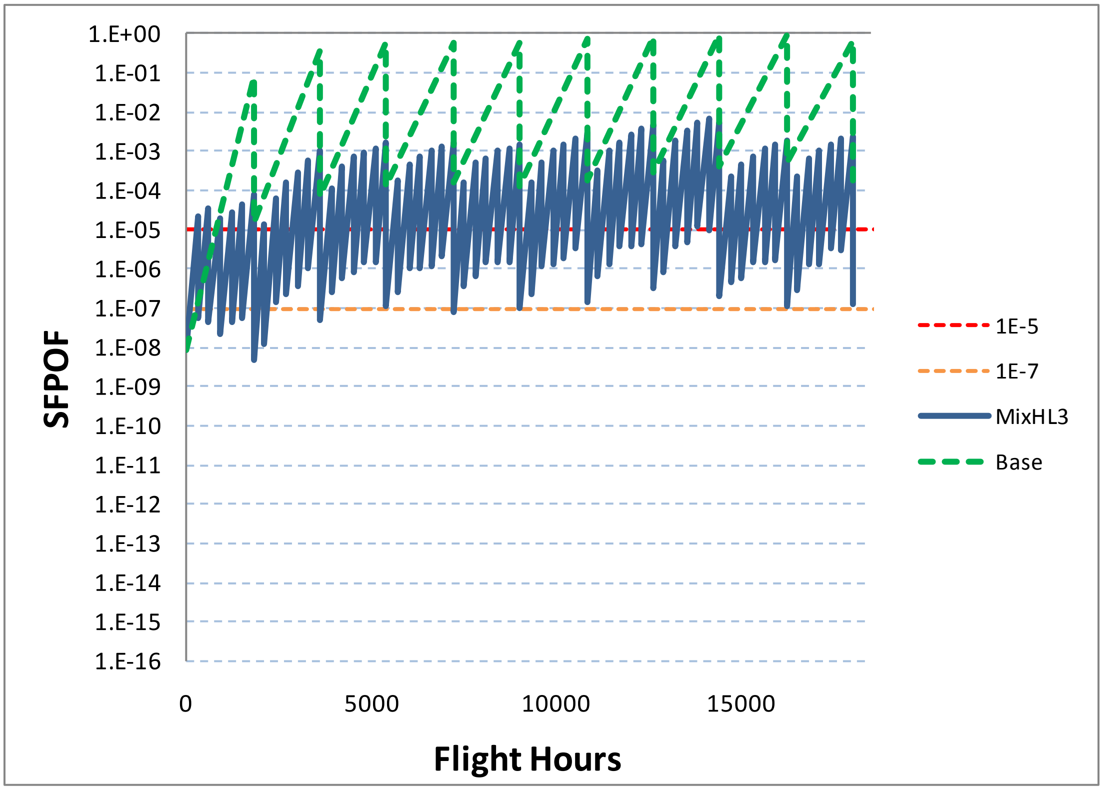


Figure 25. Baseline and Mixed Options for DTA 115

A number of methods for mitigating the high risks were attempted with mixed success. These are discussed in this section. Note that for several locations, such as DTA 115, the issue is not yet resolved.

6.5.1. Residual Stresses

It was identified that several of these locations are either cold-worked holes or are fastener holes in which interference fit fasteners are installed. Each of these methods introduces residual stresses in the control point that increase the fatigue life. The F-15 Program has traditionally represented these residual stresses in a damage tolerance analysis by reducing the initial flaw size to 0.003” from the usual rogue flaw size of 0.05”. This significantly increases the life by providing a period of time before the crack reaches the previous initial size of 0.05”. This increases the flight hour at which the critical crack size is reached.

However, in an RBDMS analysis, the final flight hour associated with the critical crack size is not relevant. Rather, the crack growth curve is used to determine how quickly to grow the EIFS distribution. That is, a crack of size 0.05” in RBDMS will grow at the same rate regardless of the initial flaw size in the crack growth table. The initial crack size workaround is an insufficient method for representing the residual stresses in the RBDMS analysis.

The F-15 Program has been working with the AFRL software PROF in recent years and has developed a method for incorporating residual stresses in the damage tolerance analysis in a fundamental way. The technical details of this method are located in Appendix A.2.

This method was used to decrease the criticality of DTA 188. Figure 26 below shows the baseline risk before and after this method was used. Even though the risk remains relatively high, clearly this method is very useful for reducing the excessive risks for those locations for which the method applies. The remaining risk for this item simply highlights the fact that the deterministic knockdown factor that is traditionally used to determine the inspection intervals is not particularly useful for reduction of risk, as the risk is not explicitly calculated at any time. Note that the after case is used in the whole of this document and analysis.

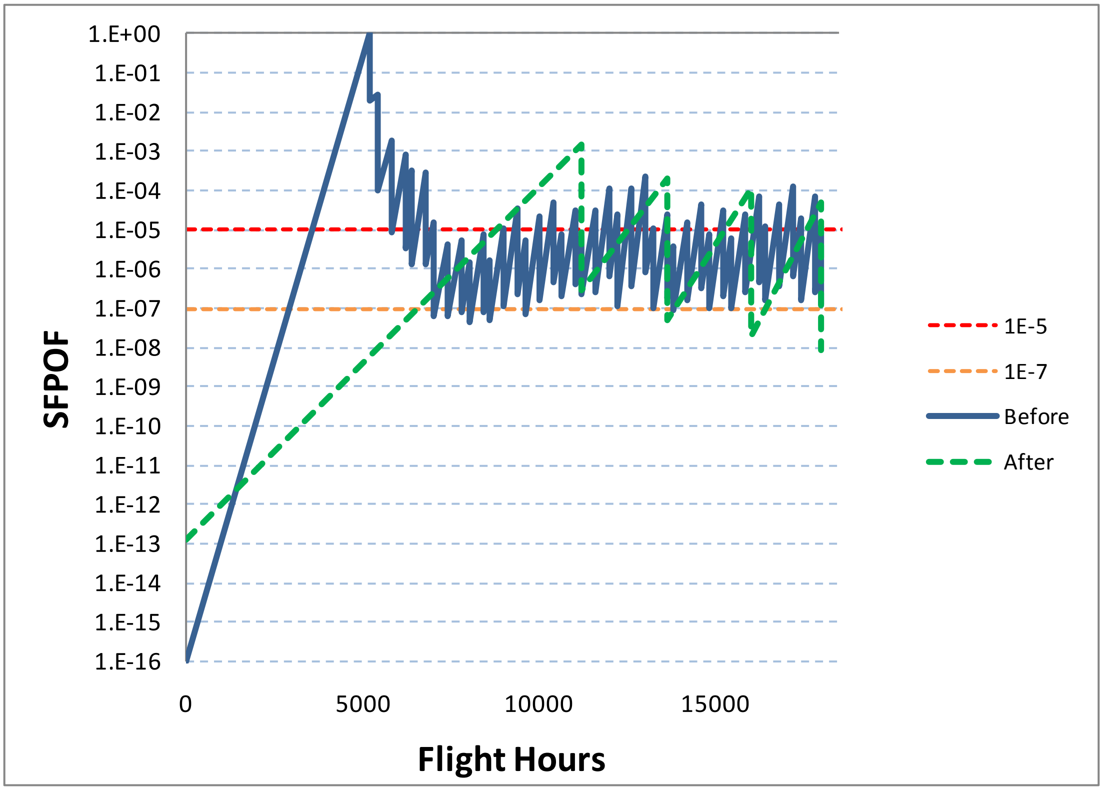


Figure 26. Baseline Risk of DTA 188 Before and After Incorporating Residual Stress

There are several other locations in the 16 location subset for which the modified crack growth analysis applies. These include DTAs 055, 164, 165, 057B, and 124B. The analysis to incorporate residual stresses for these locations has yet to be conducted. The baseline risks and associated excessively high TPM results should be significantly reduced once these modified crack growth analyses are incorporated.

6.5.2. Sensitivity Analysis

Before the residual stresses were accounted for (as discussed in the previous section) a general sensitivity analysis was conducted on two high risk DTA items (055 and 188) to determine if there was a single input or combination of inputs to RBDMS that was responsible for causing the high risks due to excessive conservatism. An attempt was made to utilize less conservative parameters for EIFS, Fracture Toughness, the spectrum, and the maximum stress distribution. The severity of each was reduced one-at-a-time and combinations were tried as well.

This analysis did not lead to any major insights and the results are therefore omitted from this report. The risks of the various modified scenarios did not identify any input parameter as the cause of the high risks.

6.6. Next Steps

6.6.1. Full Set of Locations

The analysis of the sixteen location subset is nearing completion. The next step is to perform a similar analysis for the full set of 51 Aircraft C/D wing locations.

6.6.2. NDE False Call Rate

Currently the false call rate associated with NDE inspections is assumed to be zero. This is not realistic. The team is investigating what a correct value for use in the cost model may be for the various NDE techniques employed in this study.

6.6.3. Remaining High Risk Locations

Investigation of the high risk locations that are not affected by the incorporation of residual stresses is ongoing and is being conducted on a case-by-case basis.

6.6.4. System Level Risk Assessment

Thus far in the analysis only the risk of individual components has been considered. This is an essential first step to quantifying the risk of the structural system. Additional research needs to be undertaken to determine the most accurate way to calculate the SFPOF of the wing system as a whole in order to most appropriately address the requirements of MIL-STD-1530C.

6.6.5. Sensor Degradation

Thus far the capability of the in-situ sensors used in the analysis has been considered constant throughout the lifetimes of these sensors. That is, it has been assumed that the sensors will not degrade. However, in the present cost analysis, the sensors for each location are assumed to be replaced five times within the lifespan of the design. In other words, all the sensors will be replaced on average every 12 years based on the 5 replacements in 60 years lifespan assumption. This suggests that some degradation of capability is expected to occur within these 12 year periods.

Research for the degradation model will be focused on two areas. The first is to study the sensor reliability model and determine when the most appropriate time to replace these sensors is. The second is to study the sensor degradation model and to determine its impact on the POD capability, if any.

6.6.6. Sensor Dependency

Thus far successive in-situ sensor readings used in the CBM+SI analysis have been considered independent. However, unlike the traditional infrequent NDI type of inspections, recurring inspections for an automated in-situ sensor system should be modeled as dependent due to the largely repeatable aspects of the sensor and data collection system. This dependency could impact the POD curve. Research for the dependency issue will be focused on the following areas:

- How to design the in-situ sensor system so that successive measurements are as independent as possible
- How to determine the coefficient of correlation given various environmental conditions
- How to adjust the POD curve resulting from the correlation
- How to compute the percentage of cracks detected given the correlation

7. Cost Analysis Progress

7.1. Driver Analysis

As part of any Cost Benefit Analysis a Driver Analysis must first be performed to determine what components would most benefit from health monitoring. Last March Aircraft Availability and Maintenance Hours were used as criteria for determining what components would be analyzed as part of the Cost Benefit Analysis.

7.2. Cost Benefit Analysis Tool

The Cost Benefit Analysis (CBA) Tool is an Excel spreadsheet designed to capture the operational costs due to Inspections, Repairs, and Failures of the components in consideration of a baseline system. The operational costs for alternative systems that include health monitoring are also captured along with the development and deployment of the technology. The costs of the alternative systems are each compared to the baseline system to determine the benefit of the health management system in terms of cost saving, in net present value, and also aircraft availability.

The present CBA tool is carried over from the Phase I work. The Phase I tool was extended to support additional Control Points along with new concepts of operations such as the inclusion of false calls in the cost assessments and the ability to optionally have two inspection types at a single location. With the current subset the aircraft is not permanently grounded due to failure, however, this capability has been kept in the tool for future use.

The CBA tool has 5 primary tabs which are used to calculate the costs of a single configuration. Note that there are several secondary tabs which support these tabs, and they will be discussed in the next section of this report. The primary tabs are as follows:

- Main
  - Summarizes the results of the workbook, including TPMs
- Baseline
  - Captures the operational costs of the baseline strategy for the lifecycle
- Modified
  - Captures the operational costs of the modified strategy for the lifecycle
- SHM Costs
  - Spreads the costs captured in the Baseline, Modified, and CostBreakdown tabs and determines their net present values for the lifecycle of interest
- CostBreakdown
  - Captures the costs associated with the development of the health monitoring system from requirements development through operations and sustainment

7.2.1. CostBreakdown Tab

The CostBreakdown tab buckets costs into several categories: System Design and Development, Initial Production, Production and Deployment, and finally Operating and

Sustainment. The costs are determined using engineering estimates or by similarity to existing systems.

7.2.1.1.1. System Design and Development

The System Design and Development costs for the health management system include: requirements development, system design, supplier support, prototype hardware, and qualification testing. These costs are for the on-board system and the ground system that collects and analyzes the data. The on-board costs are dependent on the number of Control Points and their similarity to one another. A ”Dependency Factor” between zero and one is used as a proxy for similarity, which is closer to one if the Control Points are very similar and closer to zero if they are very dissimilar. For a group of similar Control Points, the cost of determining requirements, design, and qualification of the health monitoring system can be shared. Our subject matter expert suggests that, for the 16 location subset utilized in this document, a Dependency Factor of 0.5 is appropriate.

7.2.1.1.2. Initial Production

The Initial Production costs are for the procurement of flight qualified hardware, installation of the health management system by Boeing personnel, initial training, and evaluation of the health management system prior to going into production.

7.2.1.1.3. Production and Deployment

The Production and Deployment costs are for the procurement of the complete sensor suite of all aircraft in the analysis and their ground stations, the installation of health management system both on-board and off-board, and some additional training of personnel. It is assumed the procurement and installation of all hardware and software occurs in the first few years of the program.

7.2.1.1.4. Operational and Sustainment

The Operational and Sustainment costs are for the collecting and storage of the health management data, replacement of sensors and ground stations, and expected software updates over the life cycle of the system.

7.2.2. Baseline Tab

The Baseline tab sums the operational costs for all Control Points of interest in terms of inspections and repairs. In the Baseline scenario there is only one inspection type: NDE. The tool requires several inputs from RBDMS and several from our local SMEs.

From RBDMS we receive the inspection intervals, SFPOF Before and After inspections, and PCD for Small, Medium, and Large cracks. SMEs provide information such as: Labor Hours/Inspection of the Control Point, additional costs and materials that may be required, NDE False Call rate, the number of similar potential failure locations in the Control Point, aircraft downtime due to inspections, and part replacement for when the damage is considered too great to be repaired. From this information the cost and aircraft downtime are calculated for each Control Point. As stated in previous sections the NDE False Call rate is currently set to zero and does not factor into the costs for this analysis.

From these inputs the tool calculates the number of flights between inspections, the probability of failure for each flight interval for the Control Points of interest, the probability of detection at each inspection of cracks of small, medium, and large sizes, the expected cost of repairs for all cracks, the number of inspections for the life of the aircraft, the costs for all the inspections, and the downtime of the aircraft for these inspections. All costs are also converted to present day dollar values for calculation of the Net Present Value.

Note that to calculate the probability of failure for each flight in an interval the tool assumes that the SFPOF increases linearly between inspections.

7.2.3. Modified Tab

The Modified tab is very similar to the Baseline tab. The most notable difference is that in the Baseline tab there is only one inspection type: NDE. In the Modified tab there are three inspection types: in-situ without accessibility penalties, in-situ with accessibility penalties, and NDE. Recall, for inaccessible locations there is a 500 man hour penalty for repairs of inaccessible locations, as well as an 8 hour downtime penalty. This is implemented by always using the first inspection type for field-accessible locations and for inaccessible locations at the depot, and always using the second inspection type for inaccessible locations away from the depot.

7.2.4. SHM Costs Tab

The costs captured on the CostBreakdown tab, Baseline tab, and Modified tab are spread across the years of implementation on the SHM Cost tab. Net Present Values are then calculated for the life of the program for both the Baseline and Modified designs.

7.2.5. Main Tab

The Main tab is use to collect the costs and downtimes calculated in the previous four tabs. The costs and downtimes are then summed and compared between the Baseline and Modified Designs. The costs are compared dollar to dollar but the downtime is used to determine the aircraft availability. The Baseline availability is pulled from reliability metrics from the service and the Modified availability is calculated from Modified systems downtime compared to the Baseline systems downtime.

7.3. Results Import Macro

The CBA tool described in the previous section calculates the TPMs for a single configuration. As stated previously, in the analysis of the 16 location subset there are 5184 in-situ configurations to consider. The task of running the many sets of results through the cost model is accomplished with a VBA (Visual Basic for Applications) macro.

Within the workbook which houses the CBA tool, three additional tabs were added to support the macro and programmatically modify the contents of the primary CBA tabs: the MACRO, DTA Info, and Configs tabs.

7.3.1. MACRO Tab

There are two tables in the MACRO tab. The first lists the options available for each DTA, along with the folder containing the RBDMS results, the results filename conventions, and the false call rates associated with each available option. See Figure 27. At this time the Baseline and Risk-based options have no false call rate associated with them. Also, note that only the Mix options have a different *Pr(FA)* for the two inspection types. For the other options, the inspection is the same in Type 1 and Type 2. However, Type 2 includes the accessibility penalties and Type 1 does not. Note that throughout the CBA the cells with a yellow background are user-modifiable, and the rest are either fixed or calculated cells.

Results Folder Path	C:\ResultsFolder		
Run Names	Filename Suffix	SHM Type 1 Pr(FA)	SHM Type 2 Pr(FA)
Base	_base.out		
Risk	_risk.out		
HF3	_HF3.out	0.01	0.01
HF6	_HF6.out	0.01	0.01
MF3	_MF3.out	0.001	0.001
MF6	_MF6.out	0.001	0.001
LF3	_LF3.out	0.00001	0.00001
LF6	_LF6.out	0.00001	0.00001
MixHL3	_MixHL3.out	0.01	0.00001
MixHL6	_MixHL6.out	0.01	0.00001
MixML3	_MixML3.out	0.001	0.00001
MixML6	_MixML6.out	0.001	0.00001

Figure 27. Available Inspection Options

The second table in the MACRO tab specifies the options selected for the 16 DTAs in the “Current Run”. The Current Run refers to the configuration that is currently being used in the remainder of the cost model. See Figure 28. The option selected for each DTA specifies both what the RBDMS results filename is called and whether this option calls for SHM or NDE. The number of SHM locations is counted in the cell at the bottom right of the figure, and this drives the count of SHM locations in the tab CostBreakdown (described in the previous section).

Current Run	DTA	Filename	NDE or SHM
LF3	dta055	dta055_LF3.out	SHM
LF6	dta057B	dta057B_LF6.out	SHM
Risk	dta097	dta097_risk.out	NDE
MixHL3	dta115	dta115_MixHL3.out	SHM
LF6	dta124B	dta124B_LF6.out	SHM
MF3	dta134B	dta134B_MF3.out	SHM
MixHL3	dta138B	dta138B_MixHL3.out	SHM
LF6	dta143	dta143_LF6.out	SHM
MF3	dta144	dta144_MF3.out	SHM
Risk	dta164	dta164_risk.out	NDE
LF3	dta165	dta165_LF3.out	SHM
Risk	dta166B	dta166B_risk.out	NDE
Risk	dta184	dta184_risk.out	NDE
Risk	dta187	dta187_risk.out	NDE
Risk	dta188	dta188_risk.out	NDE
Risk	dta203	dta203_risk.out	NDE
		# of SHM in Current Run	9

Figure 28. Current Configuration for CBA

In addition to these two tables, this sheet contains the VBA macro itself behind-the-scenes. Also, the button which instructs the macro to run is located below these tables in the MACRO tab.

7.3.2. DTA Info Tab

The information specific to each control point is located in this tab as a matrix. The values here propagate through the Baseline and Modified tabs of the CBA tool. A screenshot is omitted as this information was presented in Section 4 of this report.

7.3.3. Configs Tab

The list of configurations to be run through the macro is contained in this tab. In this tab there is a column corresponding to each DTA item and 5184 rows in which the inspection options are specified for each DTA. Additional columns are located to the right of this table for the TPM results corresponding to each configuration. The first several rows are shown below in two pieces in Figure 29. Only the first TPM, Net Present Value, is shown due to space restrictions in this document. Note that each row of this table is unique, representing one of the many configurations under consideration.

dta055	dta057	dta097	dta115	dta124	dta134	dta138	dta143	dta144
Risk	Risk	Risk	MixHL3	LF6	MF3	MixHL3	LF6	MF3
LF3	Risk	Risk	MixHL3	LF6	MF3	MixHL3	LF6	MF3
Risk	LF6	Risk	MixHL3	LF6	MF3	MixHL3	LF6	MF3
LF3	LF6	Risk	MixHL3	LF6	MF3	MixHL3	LF6	MF3

dta164	dta165	dta166	dta184	dta187	dta188	dta203		NPV
Risk	Risk	Risk	Risk	Risk	Risk	Risk		$1,787,958,197.73
Risk	Risk	Risk	Risk	Risk	Risk	Risk		$1,812,138,981.07
Risk	Risk	Risk	Risk	Risk	Risk	Risk		$1,790,023,406.36
Risk	Risk	Risk	Risk	Risk	Risk	Risk		$1,814,205,781.37

Figure 29. First Several Rows of Configs Tab

The macro starts with the first row of this table, copying and pasting the contents into the first column of the table of the MACRO tab shown in Figure 28. The results file names indicated in that table are then sequentially imported by the macro. The parameters appropriate to each option propagate through the workbook as well, ultimately calculating the TPMs. The value of each TPM associated with that configuration are then copied and pasted into the results columns of the Configs tab, such as NPV in Figure 29.

Once this has been completed for the first row, the macro moves to the second row and repeats the process. This continues until all 5184 configurations have had their results imported and their TPMs tabulated.

The macro takes approximately 22 minutes to run for 5184 configurations.

7.4. Financial Uncertainty Analysis

7.4.1. Summary of March Report

The previous progress report introduced the strategy and identified the inputs to the cost model that are to be considered random variables in the financial uncertainty analysis. Also, the report contained some preliminary results of this analysis concerning the Phase I business case.

The ultimate goal is to conduct a financial uncertainty analysis for Phase II. Because the cost model for Phase II is incomplete, it was determined that the method should be demonstrated for the completed cost model of Phase I. As the financial uncertainty analysis for Phase I has been completed, it is written up here as a stand-alone section. To follow the discussion one need not refer to the previous progress report.

7.4.2. Motivation

Phase I included a business case analysis for each of the following inspection strategies:

- Baseline
  - Current inspection methodology
- ndeRisk
  - Risk-based inspections (no SHM)
- NDESHM
  - Combined NDE/SHM strategy
- SHM300
  - SHM only w/ 300 FH intervals
- SHM400
  - SHM only w/ 400 FH intervals
- SHM500
  - SHM only w/ 500 FH intervals

The costs of the baseline strategy are known and need not be analyzed here. The ndeRisk strategy contains far less uncertainty due to the fact that there is no SHM system in use in that case. In addition to these strategies, there were two failure options in Phase I, each offering two choices:

- Number of locations where failure can occur
  - Multiple similar locations
  - Single location
- Consequence of failure
  - Loss of platform
  - Replacement of bulkhead

Of these failure options, the most realistic and conservative case is thought to be that which considers failure at multiple locations and loss of the platform in the event of failure. The financial uncertainty analysis is conducted utilizing the versions of the cost model that are associated with these options.

The original deterministic cost benefit analysis was conducted for each of the strategies using an Excel spreadsheet model. The criteria for comparison of the strategies were three Technical Performance Measures (TPMs): % Fleet Non-Mission Capable (%NMC), Life Cycle Cost (LCC), and Net Present Value (NPV). It was noted at the time of the Phase I final briefing that several of the inputs to the business case analysis are uncertain estimates for what will occur in the future.

To understand how uncertainty regarding the estimates of these input quantities may affect the results of the TPMs an analysis has been undertaken to determine the variability of the TPMs with regard to the uncertainty of the input variables.

7.4.3. Strategy

To conduct the uncertainty analysis, some means of placing probability distributions on the input variables was required. It was determined that the most straightforward method for accomplishing this was to use the Phoenix Integration software ModelCenter.

ModelCenter is capable of creating models which allow data to flow from one software application to another. In addition, Monte Carlo sampling can be performed in which a probability distribution may be assigned to one or more input variables. ModelCenter refers to this as a *probabilistic analysis*. Here, ModelCenter is used with a single application, Microsoft Excel. The input variables of the Excel-based cost model are randomized using ModelCenter and a Monte Carlo simulation is performed.

The essential strategy for performing the financial uncertainty analysis of the Phase I business case analysis is as follows:

- Identify the input variables that are uncertain
- Acquire expert opinion to define probability distributions for each input variable
- Perform a Monte Carlo simulation for each inspection strategy using ModelCenter
- Characterize the distribution of each of the three TPMs in each model
- Perform a sensitivity analysis to identify the critical model inputs
- Assess what (if any) implications this has for the business case analysis of Phase I

7.4.4. Uncertain Cost Model Input Variables

The team's SHM subject matter expert (SME) identified those cost model input variables which are uncertain estimates, and also identified the best- and worst-case values for these variables. The uncertainty analysis for each of the SHM strategies is conducted twice, utilizing two distributional assumptions for these variables. In the first case (uniform case), each cost is represented with a uniform distribution between the low and high values. In the second case (normal case), each cost is represented with a normal distribution with the mean placed evenly between the best- and worst-case values and the standard deviation chosen such that the low and high values are each two standard deviations from the mean. The SME also identified two variables that are excellent point estimates, yet still are not certain. These variables are assigned a normal distribution with 10% CoV in both the uniform and normal cases.

Lastly, the SME indicated that two variables of the original cost model are very highly correlated. These are *Complete Requirements Derivation and Design* and *Associated Engineering Costs* of sheet "CostBreakdown" in the cost model. These are assumed in this analysis to be perfectly linearly correlated. Hence the former random variable is randomized in ModelCenter, and the latter is determined within Excel utilizing a linear relationship in proportion to the original cost model estimates.

The random variables for the SHM cases are described below. The first part of the variable name indicates the sheet of the cost model where it is location. *Cost*- corresponds to sheet CostBreakdown, *Main*- to sheet Main, and *Mod*- to sheet Modified.

- CostAircraftIntegration
    - Hours required to determine how to integrate the sensors in the aircraft
- CostCompleteSensorSet
    - Hardware cost of the sensors themselves
- CostDerivationAndDesign
    - Hours required to design and develop the sensor system capability
- CostDesignValidation
    - Hours for prototyping and testing
- CostInitProdTeamMan
    - Hours of labor in the initial production period to gain confidence in the data being collected by the system
- CostMatureGroundSystem
    - Cost of off-the-shelf data acquisition system
- CostQualAndCertSupport
    - Hours preparing certification paperwork
- CostRepairReplaceSensors
    - Average number of times the sensor system will be replaced over the life
- MainInstallLaborHours
    - Hours to install the sensors themselves
- ModLaborHrsPerInspec
    - Hours required to perform an inspection
- ModLaborHrsPerRepair
    - Hours required to perform a repair
- CostMaterialsCost
    - Cost of prototype unit prototyping and testing
- CostSupplierEngEffort
    - Cost for design and building of prototype

The distributions assigned to each of the random variables for the SHM strategies of the financial uncertainty analysis are shown in Table 15 below, along with the distributions assigned for each of the two analysis cases. Note that the best- and worst-case values are often *higher* than those used in the original estimate. For this analysis it was decided that the estimated distributions should error on the side of conservatism. This will be evident when the results are presented in a later section as the distributions of the TPMs will be more or less preferable than were the original point estimates.

ModelCenter Variable Name	Units	Original Estimate	Best Case	Worst Case	Normal Mean	Normal St Dev
CostAircraftIntegration	hrs	10	8	16	12	2
CostCompleteSensorSet	$	750	500	750	625	62.5
CostDerivationAndDesign	hrs	160	160	960	560	200
CostDesignValidation	hrs	80	160	480	320	80
CostInitProdTeamMan	hrs	960	640	1280	960	160
CostMatureGroundSystem	$	5000	3000	10000	6500	1750
CostQualAndCertSupport	hrs	80	80	160	120	20
CostRepairReplaceSensors	#	2	2	5	3.5	0.75
MainInstallLaborHours	hrs	5	5	10	7.5	1.25
ModLaborHrsPerInspec	hrs	0.5	0.5	1	0.75	0.125
ModLaborHrsPerRepair	hrs	2	1.5	2.5	2	0.25
CostMaterialsCost	$	2000			2000	200
CostSupplierEngEffort	$	5000			5000	500

Table 15. Variables and Associated Distributions for SHM Strategies

In addition to the SHM strategies is the ndeRisk strategy. The uncertainty analysis for this contains fewer random variables, but is similarly conducted utilizing both uniform and normal distributional assumptions. The random variables for the ndeRisk strategy and the assigned distributions are shown in Table 16.

ModelCenter Variable Name	Units	Original Estimate	Best Case	Worst Case	Normal Mean	Normal St Dev
CostDerivationAndDesign	hrs	1920	1920	2880	2400	240
CostInitProdTeamMan	hrs	640	640	1280	960	160
ModLaborHrsPerInspec	hrs	3	3	4	3.5	0.25
ModLaborHrsPerRepair	hrs	1.5	1	2	1.5	0.25

Table 16. Variables and Associated Distributions for ndeRisk Strategy

7.4.5. TPM Results

The most important TPM is the net present value (NPV). The life cycle cost (LCC) is very similar to the NPV. The NPV considers the time value of money, but the LCC does not. Note that both NPV and LCC represent costs, that is, *lower is better*. The third TPM, percent non-mission-capable (%NMC), was shown in Phase I to be negligibly affected by the various strategies. Due to these considerations, the majority of discussion in this section refers to the NPV. For reference, Table 17 contains the totality of results for each of the TPMs.

TPM	Strategy	Uniform Mean	Uniform St Dev	Normal Mean	Normal St Dev
NPV	ndeRisk	24.692	0.120	24.692	0.102
($m)	NDESHM	15.371	0.807	15.377	0.698
	SHM300	5.703	0.839	5.698	0.702
	SHM400	5.698	0.806	5.713	0.689
	SHM500	9.115	0.805	9.158	0.678
LCC	ndeRisk	35.901	0.150	35.900	0.126
($m)	NDESHM	22.090	1.181	22.100	1.021
	SHM300	7.887	1.227	7.878	1.028
	SHM400	7.879	1.179	7.903	1.009
	SHM500	12.900	1.178	12.963	0.993
PercNMC	ndeRisk	0.0536%	0.0042%	0.0535%	0.0036%
	NDESHM	0.0187%	0.0031%	0.0188%	0.0027%
	SHM300	0.0384%	0.0066%	0.0383%	0.0057%
	SHM400	0.0309%	0.0052%	0.0305%	0.0045%
	SHM500	0.0236%	0.0040%	0.0234%	0.0035%

Table 17: All Results for Each Strategy

In Table 17 above you can see that the resulting standard deviations for each TPM are slightly lower for the normal case. This is due to the fact that the normal distribution has more weight at the mean value than does the uniform distribution.

Figure 30 and Figure 31 below depict dotplots of NPV for each of the strategies for the uniform case and normal case, respectively. Each point in the dotplot is a single realization of the Monte Carlo analysis. The values have been *jittered* vertically so that the density of the points can be easily visualized. The original point estimates of the Phase I business case analysis are shown as red on yellow diamonds in the figure. Note that in all SHM strategies the NPV is vastly preferable to that of the ndeRisk strategy. The variability of the NPV is not such that the original discoveries of the deterministic cost benefit analysis of Phase I need not be questioned.

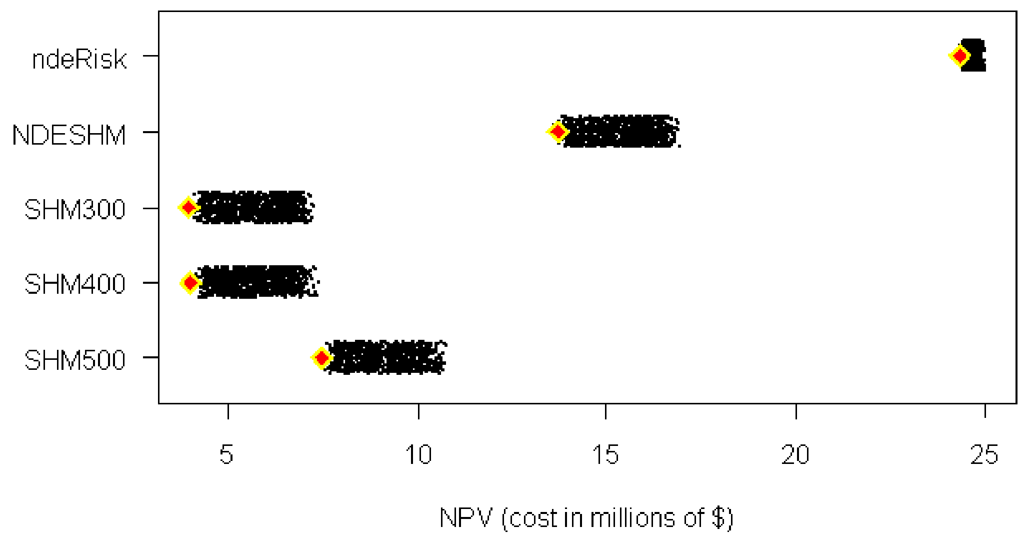


Figure 30. Dotplot of NPV; Uniform Case

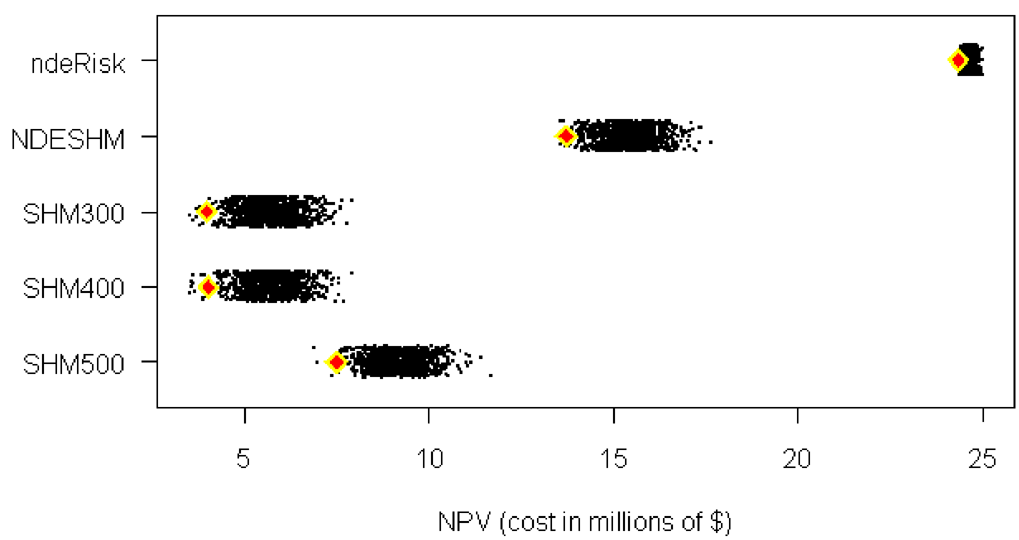


Figure 31. Dotplot of NPV; Normal Case

7.4.6. Sensitivity Analysis for NPV

To better understand the variables which drive the NPV, a sensitivity analysis was performed. The sensitivity analysis is not performed for LCC as LCC and NPV both measure costs and thus the sensitivity analyses will yield similar results. Also, this analysis was not conducted for %NMC since it is intuitively obvious which variables drive the downtime: *ModLaborHrsPerInspec*, *ModLaborHrsPerRepair*, and *MainInstallLaborHours*. Finally, this analysis was not performed for the ndeRisk case as the engineering manpower variables associated with that are considered to be well understood (in contrast to SHM development and maintenance costs).

This analysis consists first of a correlation analysis which determines which input variables are most highly linearly correlated with the NPV. Then, a multiple linear regression analysis is conducted to find the amounts by which the NPV will change for given changes in the inputs. Note that each of these assumes a linear relationship between the inputs and NPV. This linearity assumption can be validated by viewing a scatter plot of each input variable with NPV. All but one of these plots are noise for the most part as the individual correlations are not strong. A typical example is shown below in Figure 32, along with the plot of the one variable which exhibits nearly perfect linear correlation. This variable is discussed below.

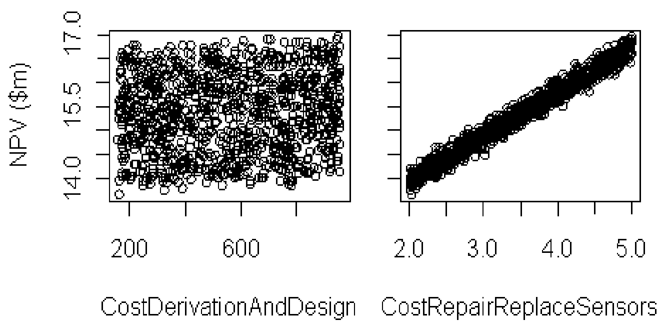


Figure 32. Scatter Plots of NPV Versus Two Input Variables

The results of the correlation analysis are shown below in Table 18. The correlations shown are known as Pearson's Correlation Coefficients, which measure the degree of linearity in a relationship. This value has a range between –1 and +1, where –1 indicates a perfect linear relationship with a negative slope, +1 indicates a perfect linear relationship with a positive slope, and 0 indicates no linear relationship.

	NDESHM	SHM300	SHM400	SHM500
CostRepairReplaceSensors	0.99	0.98	0.98	0.99
ModLaborHrsPerInspec	0.08	0.18	0.10	0.12
CostDerivationAndDesign	0.08	0.14	0.07	0.07
CostInitProdTeamMan	0.09	0.04	0.07	0.07
CostCompleteSensorSet	0.03	0.06	0.08	0.06
CostMatureGroundSystem	0.02	0.07	0.06	0.09
MainInstallLaborHours	0.03	0.02	0.04	0.05
CostDesignValidation	0.07	0.04	0.01	0.01
CostQualAndCertSupport	0.04	-0.01	0.04	0.03
CostMaterialsCost	0.02	0.04	0.03	-0.02
CostSupplierEngEffort	0.03	0.05	0.01	-0.02
CostAircraftIntegration	0.03	0.02	0.02	-0.01
ModLaborHrsPerRepair	-0.02	0.02	0.05	-0.04

Color Scale
0.99
0.84
0.70
0.55
0.40
0.26
0.11
-0.04

Table 18. Correlation Analysis of Input Variables

The variable CostRepairReplaceSensors is responsible for the majority of the variability of NPV. This is not surprising as the SME had previously indicated that the large range given between the best- and worst-case values is necessary for this variable because in-situ sensors of the type used in this analysis have simply not been utilized in the field for decades of continuous use. The conservative assumption was that one would need to replace the entire system of sensors 2 to 5 times during the life for each aircraft, which of course has a tremendous effect on the cost of maintaining the fleet. The correct value for this variable is difficult to ascertain without performing a large scale, long term experiment.

The other variable which has some significant effect in the SHM strategies is *ModLaborHrsPerInspec*. This is also understandable as this indicates the time required to perform the data download and analysis from the SHM system. Information regarding the correct value for this variable could be obtained from a relatively inexpensive experiment.

To show how the NPV changes with each input variable a multiple linear regression analysis is conducted to obtain the regression coefficients for each strategy. The regression coefficients are shown below in Table 19. Note that many of the coefficients are not altered by the strategy. The ones that change affect NPV through the inspection frequency, such as *ModLaborHrsPerInspec*.

ModelCenter Variable Name	Units	Original Estimate	NDESHM Reg Coefs	SHM300 Reg Coefs	SHM400 Reg Coefs	SHM500 Reg Coefs
CostAircraftIntegration	hrs	10	178	178	178	178
CostCompleteSensorSet	$	750	685	685	685	685
CostDerivationAndDesign	hrs	160	266	266	266	266
CostDesignValidation	hrs	80	178	178	178	178
CostInitProdTeamMan	hrs	960	339	339	339	339
CostMatureGroundSystem	$	5000	17	17	17	17
CostQualAndCertSupport	hrs	80	178	178	178	178
CostRepairReplaceSensors	#	2	918763	918763	918763	918763
MainInstallLaborHours	hrs	5	22077	22077	22077	22077
ModLaborHrsPerInspec	hrs	0.5	396406	872093	673890	515328
ModLaborHrsPerRepair	hrs	2	28037	35424	38330	27699
CostMaterialsCost	$	2000	0.987	0.987	0.987	0.987
CostSupplierEngEffort	$	5000	0.987	0.987	0.987	0.987

Table 19. Multiple Linear Regression Coefficients for NPV

The regression coefficient is the slope associated with each input variable. That is, it is the amount by which the NPV changes if the input variable is increased by one unit. The original estimate is given to assist with interpretation.

For example, the coefficient of the first variable, *CostAircraftIntegration* is $178 for all strategies. The original estimate for this variable was 10 hrs. If it turns out to take 11 hours, the net present value of costs for the fleet increases by $178 (a trivial amount). For this variable to be relevant there would need to be a gross underestimate here, on the order of hundreds of hours.

Next consider *CostRepairReplaceSensors*. The original estimate for the number of times the sensor system would need to be replaced in the life of each platform was 2. If instead the average number of replacements turns out to be 3 per aircraft, the NPV of the system increases by $918,763. This is significant. Recall the strong relationship between this variable and NPV shown in Figure 32 and Table 18 above. It is crucial that this variable be conservatively estimated in any cost benefit analysis to ensure that costs are not grossly underestimated. Some experimentation may be necessary to better estimate the durability of this type of in-situ sensor system.

7.4.7. Conclusion

This analysis has shown a method for conducting a financial uncertainty analysis for an associated cost model. In this particular example it was shown that the variability of the NPV does not have any significant implications regarding the conclusions of the Phase I business case analysis. However, the sensitivity analysis did identify that one of the input variables of the cost model, *CostRepairReplaceSensors*, was the major driver of the variability of NPV. Care should be taken when estimating this parameter in future analyses.

The financial uncertainty analysis for Phase II will commence when the cost model for that project has reached a mature level. It is the expectation of the analysis team that the method used for Phase I can be readily utilized for Phase II.

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Appendix

A.1 Control Point Information

Extensive tables of information regarding each of the 51 control points of the F-15 C/D wing systems are shown in Figure A-1 and Figure A-2.

DTA #	Access	Sim Locs	Safety Limit	DI	Delta DI	NDE POD Median	NDE POD Slope	CW or TL
054B	Field	6	9200	0.5	0.5	0.025	0.5	
054C	Field	6	8800	0.76	.74,.73,.71,.70*n	0.025	0.6	
055	Field	36	10000	0.95	0.17	0.05	0.5	TL
057B	Field	32	18200	0.95	0.17	0.05	0.5	TL
063B	Field	32	21700	0.95	0.15	0.025	0.5	CW
112B	Field	88	12100	0.95	0.09	0.025	0.5	CW
114	Field	40	7400	0.95	0.4	0.025	0.5	
116	Field	46	12000	0.95	0.6	0.025	0.5	
130B	Field	2	5200	0.95	0.09	0.025	0.5	
139	Field	116	7000	0.95	0.34	0.025	0.5	
140	Field	30	7600	0.95	0.23	0.025	0.5	
141	Field	92	3300	PDM	PDM	0.025	0.5	
142	Field	2	13900	0.95	0.51	0.025	0.5	
164	Field	154	16000	0.95	0.05	0.05	0.5	TL
165	Field	32	13500	0.95	0.06	0.05	0.5	TL
166B	Field	2	3500	0.5	0.5	0.025	0.5	
180	Field	236	25600	0.5	0.5	0.025	0.5	
184	Field	48	3300	0.5	0.17	0.025	0.5	
187	Field	134	1700	link	link	0.025	0.5	
188	Field	20	5400	0.95	0.06	0.05	0.5	TL
191	Field	6	12500	0.95	0.15	0.025	0.5	
194	Field	22	9500	0.53	0.19	0.025	0.5	
047	Depot	18	16100	0.95	0.34	0.025	0.5	
050B	Depot	76	18500	0.95	0.019	0.05	0.5	TL
052B	Depot	150	24300	0.95	0.13	0.05	0.5	TL
056	Depot	32	17300	0.95	0.12	0.05	0.5	TL
059B	Depot	74	34500	0.95	0.07	0.05	0.5	TL
089C	Depot	20	25800	0.95	0.37	0.05	0.5	TL
097	Depot	2	9000	0.5	0.5	0.025	0.5	
115	Depot	95	5100	PDM	NA	0.025	0.5	
124B	Depot	12	11100	PDM	PDM	0.05	0.5	TL
126B	Depot	40	8700	0.95	0.04	0.025	0.5	
131	Depot	96	1600	PDM	NA	0.025	0.5	
133A	Depot	60	2600	PDM	NA	0.025	0.5	
134B	Depot	8	3700	PDM	PDM	0.025	0.5	
135B	Depot	28	16900	0.95	0.3	0.025	0.5	
137B	Depot	8	7600	0.95	0.4	0.025	0.5	
138B	Depot	4	2600	PDM	NA	0.025	0.5	
143	Depot	2	4300	PDM	NA	0.025	0.5	
144	Depot	2	4100	PDM	NA	0.025	0.5	
179	Depot	236	7400	0.52	0.51, 0.50*n	0.025	0.5	
181	Depot	16	20500	1.21	0.77, 0.58*n	0.025	0.5	
182	Depot	32	12100	0.74	0.63, 0.54, 0.50*n	0.025	0.5	
183	Depot	78	21200	link	link	0.05	0.5	TL
192	Depot	12	19800	link	link	0.025	0.5	
195	Depot	46	21100	0.5	0.5	0.025	0.5	
196	Depot	6	18600	0.95	0.35	0.025	0.5	
201	Depot	32	20200	0.5	0.5	0.025	0.5	
202	Depot	18	17600	0.4	0.1	0.025	0.5	
203	Depot	2	9500	PDM	NA	0.025	0.5	
145	F/D	54	12900	0.95	0.47	0.025	0.5	

Figure A-1. Control Point Information (1 of 2)

DTA #	Max Stress Scale	Max Stress Location	Kc Mean	Kc St Dev	Material	Small Crack Threshold	Large Crack Threshold
054B	0.398	8.373	32.2	3.22	A	0.05	NA
054C	0.398	8.373	32.2	3.22	A	0.05	NA
055	1.017	21.420	45.2	4.52	A	0.05	0.25
057B	1.017	21.420	45.2	4.52	A	0.05	0.25
063B	0.431	9.070	32.2	3.22	A	0.05	0.25
112B	1.046	22.020	32.2	3.22	A	0.05	0.25
114	0.360	7.580	39.2	3.92	A	0.05	0.25
116	0.346	7.290	32.2	3.22	A	0.05	0.25
130B	0.829	17.450	32.2	3.22	A	0.05	0.25
139	0.892	18.780	32.2	3.22	A	0.05	0.25
140	1.100	23.160	32.2	3.22	A	0.05	0.25
141	0.296	6.220	32.2	3.22	A	0.05	0.25
142	5.534	116.510	32.2	3.22	A	0.25	NA
164	1.459	30.710	100.2	10.02	T	0.05	0.25
165	1.418	29.860	100.2	10.02	T	0.05	0.25
166B	1.529	32.190	100.2	10.02	T	0.05	0.25
180	0.050	1.080	32.2	3.22	A	0.05	0.25
184	1.584	33.360	39.2	3.92	A	0.05	0.25
187	0.952	20.050	39.2	3.92	A	0.05	0.25
188	0.047	0.990	39.2	3.92	A	0.05	0.25
191	4.232	89.100	39.2	3.92	A	0.05	0.05
194	0.061	1.290	32.2	3.22	A	0.05	0.25
047	3.27	68.78	100.2	10.02	T	0.05	0.05
050B	0.04	0.87	100.2	10.02	T	0.05	0.25
052B	0.04	0.78	100.2	10.02	T	0.05	0.25
056	0.869	18.3	45.2	4.52	A	0.05	0.25
059B	0.031	1.4	45.2	4.52	A	0.05	0.25
089C	6.16	5.03	100.2	10.02	T	0.2	0.4
097	1.44	30.42	100.2	10.02	T	0.05	0.05
115	0.772	16.25	32.2	3.22	A	0.05	0.25
124B	0.55	11.58	45.2	4.52	A	0.05	0.25
126B	1.158	28.09	39.2	3.92	A	0.05	0.25
131	1.157	24.37	32.2	3.22	A	0.05	0.25
133A	2.586	54.45	32.2	3.22	A	0.05	NA
134B	1.033	21.75	45.2	4.52	A	0.05	0.25
135B	6.035	127	45.2	4.52	A	0.05	0.25
137B	3.447	72.57	45.2	4.52	A	0.05	0.25
138B	1.095	23.05	45.2	4.52	A	0.05	0.25
143	3.774	79.45	80	8	A	0.05	0.25
144	0.333	7.01	39.2	3.92	A	0.05	0.25
179	0.06	1.27	32.2	3.22	A	0.05	0.25
181	0.062	1.3	30	3	A	0.05	0.25
182	0.051	1.08	45.2	4.52	A	0.05	0.25
183	0.046	0.97	100.2	10.02	T	0.05	0.05
192	0.086	1.81	45.2	4.52	A	0.05	0.25
195	0.049	1.04	45.2	4.52	A	0.05	0.25
196	4.228	89.02	45.2	4.52	A	0.05	0.25
201	5.187	109.2	45.2	4.52	A	0.05	0.25
202	2.69	56.6	45.2	4.52	A	0.05	0.25
203	0.05	1.06	45.2	4.52	A	0.05	0.25
145	1.287	27.1	39.2	3.92	A	0.05	0.25

Figure A-2. Control Point Information (2 of 2)

A.2 F-15 Methodology for Inclusion of Residuals Stresses in Crack Growth Analysis Due to Cold Working or Interference Fit Fasteners

The current methodology on the F-15 program to account for residual stresses due to interference fit fasteners or cold worked holes is conservative. The initial flaw size is decreased in the crack growth analysis from a 0.05” corner flaw to a 0.005” corner flaw and no residual stresses are used from cold working or interference fit fasteners. This is a conservative approach compared to actually using mechanically induced residual stresses as part of the crack growth loading profile. This has been done historically as it was assumed that control of cold working or installation of interference fit fasteners in large areas (such as the lower wing skin) may not be maintained.

This approach presents a problem for the risk assessment tool PROF. The assumed initial flaw size in a PROF risk assessment is 0.003” (based on an Equivalent Initial Flaw Size approach). For normal fastener holes, a change from an initial flaw of 0.05” to 0.003” provides a relatively large increase in life. But when the flaw size only changes from 0.005” to 0.003” the crack growth life has only a small change. This causes the risk assessment to be exceptionally severe.

To include residual stresses in crack growth analysis, the Finite Element program StressCheck is used. StressCheck can handle non-linear incremental plasticity analysis which can accurately determine residual stresses due to loading/unloading that is seen when cold working a hole or cycling an interference fit fastener. For the analysis provided, all holes are assessed as if they are cold worked in the StressCheck program. Analysis for interference fasteners requires additional steps that cold working does not, increasing the analysis time, which is not felt justified. Cold working results are more conservative than interference fit fastener results because of the large hole propping effect associated with interference fit fasteners. For this reason, only the method of obtaining residual stresses for cold worked holes is presented in this document.

The image below shows a typical StressCheck planar model that would be used to extract a residual stress gradient. The plate material is modeled with bilinear material properties and the fastener element is given an isotropic steel property. A linear run is performed with an initial interference (the minimum interference as defined in the Boeing Process Specification for a given fastener size). Once the linear run is complete, an incremental non-linear analysis is performed with two steps: mandrel in and mandrel out.

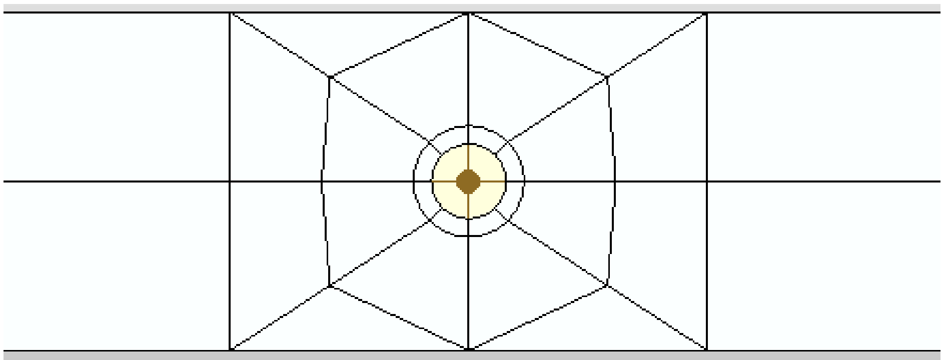

Figure A-3. Stress Check Detail

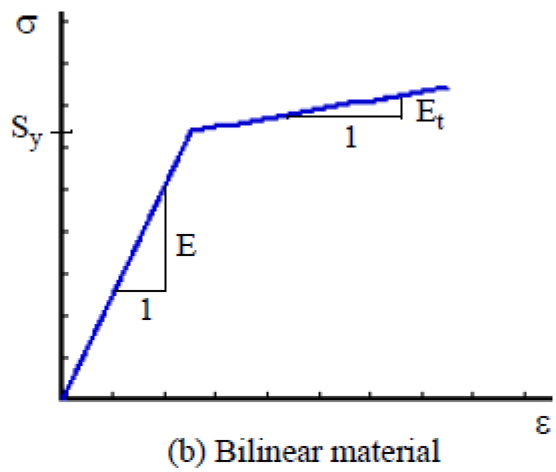

Figure A-4. Bi-linear Stress-Strain Diagram

Bilinear material properties are chosen instead of other material properties (such as Ramberg-Osgood) since bilinear material properties in planar analysis can accept a parameter to control the hardening law.

Many engineering materials when cycled repeatedly exhibit kinematic hardening behavior. StressCheck however, requires all planar non-linear materials to use an isotropic hardening law except for the bilinear material property where it can be specified. Consequently, bilinear material properties are used.

Once the analysis is complete, a stress gradient of the tangential residual stresses is taken from the hole wall to the edge of the part. These residual stresses are input into LifeWorks as a residual stress gradient and used in the analysis. The flaw then starts from the standard 0.05" but has the benefit of residual stresses included. See Figure A-5 below.

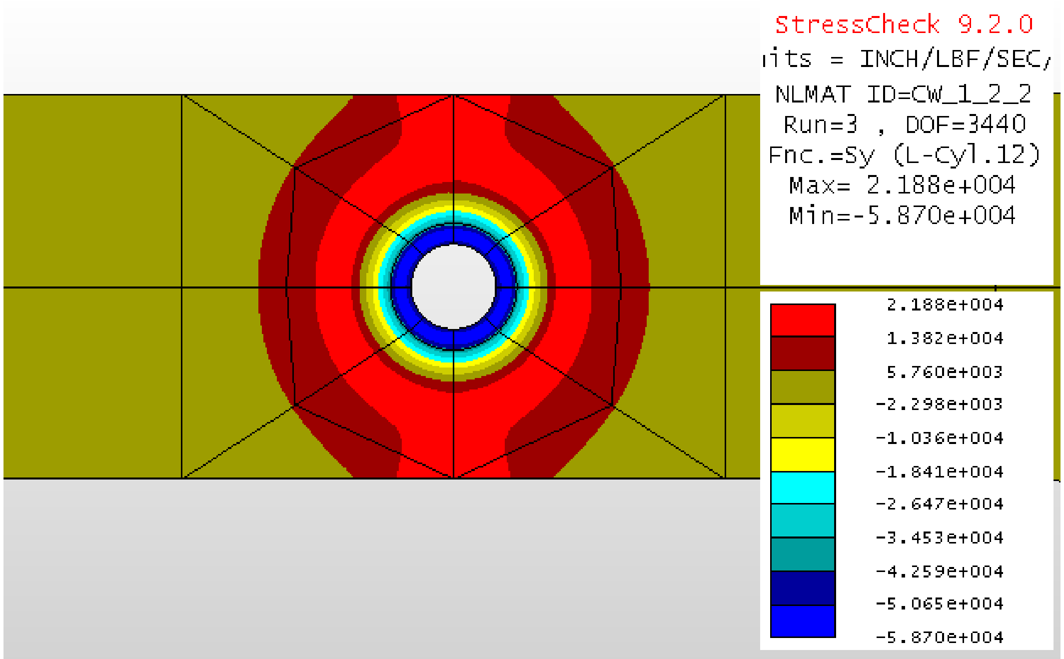

Figure A-5. Stress Check Result

A.3 RBDMS Modifications

1. SFPOF system reliability calculation formula has been modified.
    a. For the system reliability calculation, the RBDMS code applied the same formula used by the PROF code. The simple formula used was to multiply the calculated risk with the number of locations; this is actually an approximation formula and it is only good for the problems with smaller risk. When the risk is getting larger, this approximation formula may be incorrect and it can yield unreasonable SFPOF value (i.e., >1).
    b. To modify the potential mistake, the RBDMS code has been modified by using the following formula:

    SFPOF(system) = 1 – (1 – SFPOF(component))^(number of Similar Locations)

2. For each location (control point), more than one inspection type (i.e., multiple PODs) for both field inspection and program depot maintenance (PDM) inspection can be considered and input.
    a. The purpose of developing this capability is to accommodate potential multiple inspection types for the same location. A potential scenario is to use a POD with lower fidelity to detect the cracks during the field inspection and then use a POD with higher fidelity to detect the cracks during PDM. This capability will greatly enhance the reality of our cost analysis model by accurately calculating the Percentage of Cracks Detected (PCD) data for various PODs used.
    b. To accommodate this capability, the RBDMS code's "POD" input file format has been modified and the PODs must be properly stored for the computation of the

PCD. The math computation method and code for the PCD remain unchanged because only POD parameters have been modified.

3. For each inspection, more than one POD types can be selected and used to compute the percentage of crack detected (PCD).
    a. The purpose of developing this capability is similar to those described in item 2 above.
    b. To accommodate this capability, the RBDMS code's "inspection" input file format has been modified and the "inspection" options must be properly stored for computation of the PCD. The math computation method and code for the PCD remain unchanged because only POD parameters have been modified.

4. For each inspection, the PCD will be calculated and subdivided into small, median, and large crack zones so different repair strategies can be applied.
    a. The purpose of this new capability is to compute the PCDs for the various repair strategies. When the identified crack size is smaller, a simple reaming process can be applied; however, when the crack size is larger, a more costly or time-consuming repair strategy needs to be applied. With this capability, the repair cost can be calculated with higher fidelity.
    b. For this new capability, the user must determine two crack sizes ($a1$ and $a2$) and input these data for the RBDMS code to compute the PCDSmall ($a < a1$), PCDMedian ($a1 < a < a2$), and PCDLarge ($a > a2$). The input file of the RBDMS code needs to be changed accordingly to input the two crack sizes. The code to calculate the PCD has been modified to subdivide the original calculated PCD into three pieces as described above by properly managing the PCD data. The math computation method and code for the PCD remain unchanged.

5. A new summary output file with all the necessary data for the cost analysis has been defined and developed.
    a. The purpose of this summary file is to provide a tabular format of all the key output data so it can be easily read in by the cost analysis code. Previously, the cost analysis code had to read in several output files.
    b. To record these data, only some bookkeeping of these output data are required and there are no changes for the math computation method and code. A new RBDMStable.out has been created to store these data by the RBDMS code.

6. The crack growth and geometry data input files have been modified for the RBDMS code.
    a. At present, to run the RBDMS code, it is necessary to modify both the crack growth and geometry data files by inserting two additional lines and modifying one line. The first line is to add a line for the total no. of data pairs and the second line is to add a line of (0., 0.) as the starting point for the crack growth computation. Then, it needs to modify the original first line of the input data (a1, t1) and change it to (a1, t1/2). Therefore, the purpose of this task is to reduce the modifications as much as possible so it will be easier for the user to use the RBDMS code.

b. To meet the needs, the RBDMS code has been modified to accept both the crack growth and the geometry files with only one modification still needed. For both the crack growth and the geometry files, the user only needs to input the line with the total no. of data pairs. Without this line, the RBDMS code will have difficulty reading in the data pairs correctly. There are no changes for the math computation method and code and the modified code has the capability to read in the following two options:
    i. Option one will be the current case: For the crack growth data file, the user needs to add a line of the total number of input data pairs, a data pair (0., 0.), and then modify the original first line of the input data as described above. For the geometry file, user also needs to input the total number of input data pairs, a data pair (0., 0.), and then modify the original first line of the input data as described above.
    ii. Option two will be the newer option. For this option, user only needs to input a line of the total number of input data pairs for both the crack growth data file and the geometry file. There is no need to add/modify the other data.

7. A computation error occurred for both RBDMS and PROF codes when the EIFS distribution has the crack size larger than the critical crack length used in the crack growth curve data (for example, DTAs 130, 131, 133A, and 145). The RBDMS code has been modified to resolve this problem and issue a warning sign for this type of problems.
    a. When this type of problem has been identified, first, a warning message will be shown in the output data file to advise user to check their input data especially the EIFS and CG curve data. Normally, the EIFS data should be much smaller than the critical crack length.
    b. For the RBDMS code to resolve this problem, an artificial data pair with the crack length longer than the critical crack length was added for the risk computation purpose. A new limit for the artificial crack length has been modified so it can be automatically increased to avoid this type of errors, i.e., when the initial crack size is larger than the critical crack length. The potential problem for this modification is that the extended crack length can be unreasonable compared to the actual structure data. That is the reason why it needs to provide the warning message for user to check the input data. The math computation method and code for the SFPOF remain unchanged because of this modification.

8. A time zero SFPOF calculation has been implemented so it can be used in cost analysis.
    a. The purpose is to compute the time zero SFPOF so user can compare if this is starting from a very small initial crack size distribution. It is a good starting data point for the cost analysis as well.
    b. To accommodate this capability, the input file will not be changed but the code has been modified so it can automatically compute the time zero SFPOF. The math computation method and code for this new capability remain unchanged. The key is to properly manage the code by introducing an additional computation of SFPOF at time zero where the initial crack size distribution will be used as the

crack size distribution for the SFPOF computation. The output file for this new capability has been modified accordingly.

9. The output file names have been modified so it can be read easily.
    a. Change the other output file names so it can be read easily. The RBDMS code has been modified accordingly. The math computation method and code for this new capability remain unchanged.
    b. The following output file names have been changed:
        i. Plot1.out to RBDMSdists.out
        ii. Plot2.out to SFPOF.out
        iii. Plot3.out to PCDall.out
        iv. Plot31.out to PCDsmall.out
        v. Plot32.out to PCDlarge.out
        vi. Plot11.out to RBDMStable.out